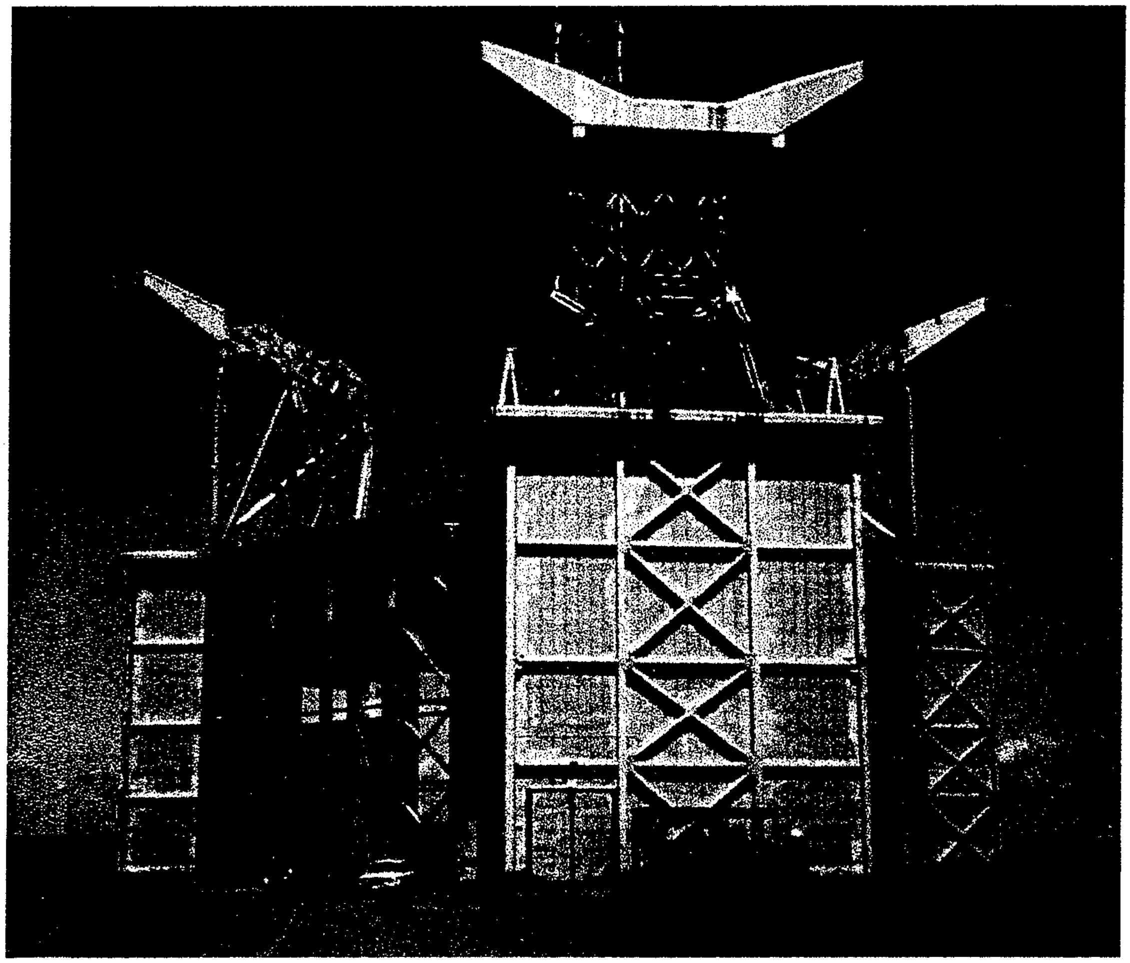

TECHNICAL REPORT 1761
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VLF Cutler: September 1997 Four-Panel Tests; RADHAZ and Field Strength Measurement

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ADMINISTRATIVE INFORMATION

The work detailed in this report was performed for the Naval Computer and Telecommunications Command, Code N42C, by the Electromagnetics and Advanced Technology Division, Space and Naval Warfare (SPAWAR) Systems Center, San Diego (SSC San Diego).

Released by
J. W. Rockway, Technical Staff
Electromagnetics and Advanced
Technology Division

Under authority of
C. J. Sayre, Head
Electromagnetics and
Advanced Technology
Division

ACKNOWLEDGMENTS

The tests described in this report resulted in a highly unusual set of circumstances for the crew of naval radio transmitting Station Cutler, Maine. The tests could not have been accomplished had not the crew supported us in a highly professional manner that required efforts far in excess of those required for normal operation. The primary crews involved in this test were the antenna mechanics and the operators and electronic technicians that support transmitter operations. All personnel provided outstanding support to us during this test.

In particular, this author was more involved with the antenna maintenance personnel and would like to especially acknowledge their efforts. During this test period they successfully accomplished every task asked of them. Very often, these were highly unusual, never having been done before. In addition, many of them were on short notice or required in-process changes.

Their efforts greatly contributed to the success of this test. An example of this is that they worked out a technique for tap changing that could be done rapidly to accommodate the required recall time. Also, early in the four-panel test an insulator failed, taking the station off the air and jeopardizing the entire test. The antenna mechanics were instrumental in rapidly isolating the failed insulator and getting the station back on the air in four-panel mode with different panels. They then worked out a technique for replacing the failed insulator with no downtime, which enabled us to complete the tests.

Peder Hansen
San Diego, CA
6 November 1997

EXECUTIVE SUMMARY

BACKGROUND

The Navy's very-low-frequency (VLF) station at Cutler Maine provides communication to the United States strategic submarine forces. The antenna consists of two completely separate arrays designated the north array and the south array. Each array consists of six diamond-shaped panels supported by 13 towers. The system was designed to allow transmission by one array (single) or both arrays (dual). Antenna maintenance is performed during the summer months by transmitting on one array while working on the other array, which is grounded. This allows continuous transmission, crucially important since the Navy closed Annapolis, the only other East Coast station.

The region where the two arrays come close together is called the bow-tie area. There are two panels and three towers from each array in this area. The fields on the grounded array are highest in the bow-tie area due to proximity to the active array. The present station operating procedure, based on a past RADHAZ survey, does not allow work on the bow-tie area towers or panels while transmitting on the other array. There is an ongoing tower painting project at Cutler scheduled for completion over the next few years. Under the present station policy, completion of this project would require several months of total downtime, now unacceptable.

OBJECTIVE

The objective of the four-panel tests was to provide VLF Cutler with the capability of performing the special painting project and normal maintenance on the bow-tie area towers of an inactive array while transmitting with the other array. A secondary objective was to determine the antenna operating parameters which had not been measured since changing to 24.0 kHz.

APPROACH

Tests were conducted at Cutler to determine if the bow-tie towers of one array could be safely worked on with the other antenna having four active panels and the two nearest panels to the fires array inactive. In addition, the performance of the antenna and transmitter when operated was determined and compared to that for six-panel operation. The tests took place during a two-week period from 8 to 22 September 1997. During this time, the north array was inactive, undergoing painting and helix house repairs.

The test team included members from NRaD, NMRI Det., and PSR Corp. as well as on-site personnel. The following measurements were obtained during the test period while transmitting in both six-panel and four-panel mode: (1) antenna impedance; (2) field strength survey to determine radiated power; (3) radiation hazard survey on the bow-tie towers of the north array; and (4) radiation hazard around the south array. Tests of the transmitter operating parameters are reported elsewhere. All measurements were made while transmitting on the south array at 24.0 kHz with the north array grounded. The results of the radiation hazard measurements should apply equally well when transmitting with the north array due to the symmetrical design of the two antennas.

FINDINGS

Antenna Measurements

The results of the antenna measurements for the south array are given in table ES-1.

Table ES-1. South array antenna measurement results.

	Six-Panel Mode	Four-Panel Mode
Antenna effective height (m)	140.1 ± 2.8	130.4 ± 2.6
Antenna self resonance (kHz)	40.2	40.0
Antenna static capacitance (nF)	123.9	90.1
Gross resistance (ohms) measured at full power	0.2649	0.2675
Radiation resistance (ohms)	0.1984 ± 0.0077	0.1719 ± 0.0068
Antenna base reactance (ohms)	-j 35.4	-j 50.2
Antenna bandwidth (Hz) measured at low power	137.5	100
Antenna radiation efficiency (%)	74.9 %	64.3 %
Base voltage (kV)	65.5	99.7
Base current (A)	1850	1987
Radiated power (kW)	679	679

The GPSS coordinates for the south tower zero are provided in table ES-2.

Table ES-2. Cutler south array tower zero, GPSS coordinates.

Latitude	Longitude
4° 38.240' north	67° 16.713' west

RADIATION HAZARD MEASUREMENTS

In the frequency range from 3 to 100 kHz, the Navy has adopted the American National Standards Institute (ANSI) standard regarding exposure to electromagnetic fields. This standard allows exposure to electric fields with strengths up to 614 V/m. For controlled areas, such as the VLF transmitting area at Cutler, the standard includes an important exclusion allowing for exposure to higher fields under certain conditions. Conservatively stated, the exclusion allows exposure to higher fields if body current through a limb (in mA) is numerically less than the operating frequency in kHz. At the Cutler operating frequency, this amounts to 24 mA through a limb.

Note that the findings, conclusions, and recommendations given below are only valid for operation on 24.0 kHz with 679 kW radiated power or less.

Six-Panel Operation

(1) Bow-tie towers

(a) Fields inside and outside the bow-tie towers were below the safe exposure limit of 614 V/m everywhere, except on the top of towers N5, and N7, where minor (nuisance) shocks were experienced .

(b) Body current measurements verified that all normal maintenance procedures can be accomplished in six-panel mode.

(2) Simulated winch

(a) Voltages and currents were within safe limits except if a person is in series in the loop formed by the winch cable.

(3) South array vicinity

(a) The fields measured under all the feed-cages were less than 614 V/m.

(b) The fields measured under all panels were much less than 614 V/m.

Four-Panel Operation

(1) Bow-tie towers

(a) The fields inside and outside the bow-tie towers were reduced considerably by changing from six-panel to four-panel mode. Minor nuisance shocks were observed only when standing on the top of towers N5 and N7 in four-panel mode.

(2) Simulated winch

(a) The winch cable currents were below the hazard limit in four-panel mode.

(3) South array vicinity

(a) The fields measured under all active feed-cages exceeded 614 V/m in four-panel mode.

(b) Body current measurements verified that it would be safe for personnel to access the area under the active feed-cages in four-panel mode.

(c) The fields measured under all panels were considerably less than 614 V/m in four-panel mode.

CONCLUSIONS

The antenna parameters for the south array in single mode have been accurately measured on 24.0 kHz for six-panel and four-panel mode, as summarized in table ES-1. North array measurements were not obtained. Until measured, the best estimates for the north array parameters are the same as given for the south array.

In six-panel mode, the normal operating current of 1850 amps results in 679 kW radiated power and a base voltage of 65.5 kV. Maximum possible radiated power was not determined for this mode.

Appropriate procedures for mode grounding and the helix tap position selection were verified for four-panel mode. The four-panel mode should only be configured by grounding the two panels that are connected to a single bushing (i.e., one entire division of the antenna).

In four-panel mode, with the reactor operating, the same power can be radiated as normally radiated in six-panel mode. The antenna current required for radiating this power is 1984 amps, which results in a base voltage of 99.6 kV. The maximum possible radiated power was not determined for this mode.

(5) In four-panel mode, without the reactor, the radiated power is limited to 523 kW with an antenna current of 1750 amps, which results in a base voltage of 87.9 kV.
(6) In six-panel mode, the bow-tie area towers can be safely accessed everywhere to conduct normal maintenance. Nuisance shocks were only experienced by persons completely exposed while standing on the top of the N5 and N7 towers. Therefore, personnel should not stand on top of these towers while transmitting in six-panel mode. (Similarly personnel should not stand on top of S1 or S11 when the north array is transmitting in six-panel mode.) There were no nuisance shocks experienced by personnel on tower N4.

(7) A simple winch, rigged as described later in the text, using proper safety and grounding procedures, can be safely installed and operated on the bow-tie towers of the inactive array with the other array operated in six-panel mode. The rigging used by the painting contractor on-site is much more complicated than that simulated for this test. It should only be installed and operated on the bow-tie towers when in four-panel mode. Since it was not simulated, the safety of this rig should be verified prior to unsupervised operation by a contractor. The primary concern is that currents in the winch and support cables can damage the rigging if proper grounding techniques are not applied at sheaves and other contact points.

(8) In four-panel mode the electric field under the horizontal feeders near the helix house were somewhat above the maximum permissible exposure limit. However, the measured body currents through an individuals feet were less than 24 mA. Therefore, the exclusion applies and personnel can be safely allowed normal access to this area. However, they should be made aware of the possibility of nuisance shock, especially when touching rubber tired vehicles. The intensity of these shocks may be greater when the ground is wet.

(9) In both six-panel and four-panel mode the fields inside of the bow-tie towers are very low. Based on these results and our experience with the similar towers at Holt, it is probable that all towers in an active array can be safely climbed to all heights, except perhaps tower zero, as long as personnel remain inside of the tower. After verification by measurement this will allow increased antenna maintenance under the constraint of 30-minute recall (see recommendation # 5).

RECOMMENDATIONS

(1) Adopt the measured antenna parameters, summarized in table ES-1 as the official values for the south array when operated in single-array mode with the north array inactive.

(2) Revise station policy for tower access to reflect that all normal maintenance procedures can be carried out on all towers of the inactive array, including the bow-tie towers, when the other array is operated in either six-panel or four-panel mode.

(3) Use the four-panel mode, configured as described later in the text, for any special maintenance procedures on the bow-tie towers that require significant rigging, such as special painting projects, or that require standing or significant exposure time on the top of towers N5 and N7, or conversely towers S1 and S11.

(4) At the beginning of the bow-tie tower painting project verify the electromagnetic safety of the rigging by inspecting grounding techniques and measuring voltages and currents in the rigging cables. The worst case tower (N5 or S1) should be rigged first for verification. The primary objective is to ensure that the contractor follows proper grounding procedures to eliminate the danger of rigging damage due to RF currents.

(5) Verify by field strength and body current measurements that the towers of the active array can be climbed to all heights as long as personnel remain inside the tower.

(6) Measure the antenna parameters for the north array in six-panel mode and four-panel mode with the south array inactive and the dual array parameters for 24.0 kHz operation. Until they are measured, south array parameters should be used as estimates for north array parameters.

(7) Determine maximum power on both arrays at 24.0 kHz in both the six and the four-panel mode.

(8) Organize a test, to be conducted next summer, following completion of the existing painting project, to address the previous three recommendations.

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BACKGROUND

The U.S. Navy's very-low-frequency (VLF) antenna at Cutler, Maine consists of two separate antenna arrays, known as the north array and the south array. The antennas are top-loaded monopoles, each with its own separate helix house for tuning. Transmission is possible using either one array (single array mode) or both arrays (dual array mode). The top-load on each array consists of six diamond-shaped panels made up of cables and supported by halyards from 13 grounded towers. Cutler is on the coast of Maine and the antennas often experience heavy icing during the winter. Each array can be connected to a 60-Hz power source for deicing when not transmitting. The reason for the two-array design is to enable continuous transmission during periods of icing by alternately deicing one array while transmitting on the other array.

Antenna maintenance is performed during the summer months by transmitting on one array (single array mode) while working on the other array while it is grounded. This allows transmissions to continue during maintenance, which is important since the Navy closed the VLF station at Annapolis. VLF Cutler has one 12-hour down period every Monday for maintenance.

The area where the two antennas are nearest is called the bow-tie area. Two panels and three towers from each array are in this area. Some years ago, when the station operated at 17.8 kHz (vice 24.0 kHz, presently), radiation hazard measurements were made on the towers (Hagaman, 1983). The conclusion reached from this effort was that there was a potential safety hazard to personnel above the 200-foot level on towers in the active array or in the bow-tie area towers in the inactive array, while the other 10 towers in the inactive array were safe at any height. This is the station operating procedure at the present time. The present station operating procedure allows the two bow-tie area top-load panels in the inactive array to be lowered or raised while the other antenna is active, but cables or insulators in that panel cannot be disconnected. Thus, work on the bow-tie area towers and panels requires that Cutler be taken off the air.

Tower painting is ongoing at Cutler and scheduled for completion in several years. Past tower painting projects were completed with minimal impact on Cutler availability by painting the bow-tie towers during the weekly scheduled downtime. The painting project now underway involves water blasting to clean off the old paint, followed by spraying on new paint. This requires rigging the towers with moveable scaffolds and covering parts of the tower to catch the blasting and spraying residues. In the bow-tie area, this process, under present station operating procedures, would require several months of total downtime, which is operationally unacceptable since the VLF Annapolis transmitter is closed.

The proposed solution is to operate the active array in four-panel mode with the two bow-tie panels disconnected and grounded where their feed comes to the helix house roof. These two panels are the primary source of the strong electric fields on the bow-tie towers of the other array because they are closest to that array. When these two panels are inactive and grounded, the primary source of those fields is eliminated, and the grounded panels act as a shield for the fields from the remaining active panels, thereby greatly reducing the fields on the bow-tie towers.

The Navy's VLF antenna at H. E. Holt in western Australia is a scaled-up version of a single Cutler array. At VLF Holt, four-panel (or five-panel) operation is the standard operating procedure used for antenna maintenance. Recently, a RADHAZ survey was done at Holt and based on the results (Hansen & Chavez, 1993), we believe that four-panel operation at Cutler can reduce the fields on the

bow-tie towers to a level that will safely allow them to be worked on while Cutler is transmitting. Four-panel operation at Cutler is not new since it was once tested there long ago (Beauchamp, 1997).

Reducing the number of panels in operation has several deleterious effects. The bandwidth and radiation efficiency decrease, while the voltage and current increase to radiate a given amount of power. Also, the antenna reactance increases, which requires changing the antenna tuning in the helix house. These effects increase as the frequency decreases. The Cutler design frequency range is 14.3 to 30.0 kHz. Cutler's present operating frequency, 24.0 kHz, is in the upper portion of the design frequency range and calculations indicate that the system could be configured to operate adequately in four-panel mode while radiating the same amount of power presently radiated in six-panel mode.

The downtime required to rig the four-panel configuration was expected to be less than 4 hours once all the details are worked out. Consequently, an array could easily be converted from six-panel to four-panel operation or vice versa on a normal down day. Thus, large amounts of total downtime can be avoided, if it can be shown that painting and other normal maintenance operations can be done on the bow-tie area towers while operating the other array in four-panel mode.

OBJECTIVES

The overall objective of the tests was to verify that the bow-tie towers of the inactive array could be safely worked on when the antenna was operated in four-panel mode.

There were several secondary objectives: (1) to establish an efficient method for converting from six-panel to four-panel mode;. this required developing a method of disconnecting and grounding the panels, as well as making changes to the taps and settings in the helix house; (2) to verify the transmitter operation and radiated power level, including operation with and without the reactor, as well as operation with the emergency combiner; (3) to establish that personnel were safe from hazardous fields and currents while working on the bow-tie towers; to develop special techniques for working on the towers and verify their effectiveness through measurements.

A field strength survey to determine radiated power, radiation resistance, and antenna effective height had not been done at Cutler since switching to 24.0 kHz in 1985, nor had there been antenna resistance measurements at power. Thus, another secondary test objective was to determine the magnitude of the radiated power and antenna radiation efficiency in both four-panel and six-panel modes.

APPROACH

Several steps were required to conduct the four-panel tests. A number of individuals participated in the test. These individuals were of various disciplines and helped ensure the validity of the test results. The team consisted of people from the Space and Naval Warfare Systems Center, San Diego (formerly, Naval Command Control and Ocean Surveillance Center Research, Development, Test and Evaluation Division); radiation hazard experts from the Naval Medical Research Institute Detachment (NMRI Det.), Brooks Air Force Base, TX; and transmitter and measurement expert personnel from the San Diego office of Pacific Sierra Research Corporation. There were also many people involved from the Naval Radio Transmitting Station (NRTS), Cutler, Maine.

The general approach for the tests is outlined below. Note that for all these tests the south array was active while the north array was inactive and grounded.

1. Measure the radiated power, antenna effective height, and radiation resistance in the normal single array (six-panel) mode at 24.0 kHz.
2. Measure the radiation hazard fields on the ground around the active array and on the bow-tie towers of the inactive array in six-panel mode.
3. Ground two elevated panels at the feed point of the active array.
4. Adjust the helix house and transmitter settings for four-panel mode. This involves changing the tap of the helix.
5. Measure the radiated power, antenna effective height, and radiation resistance in four-panel mode.
6. Measure the radiation hazard fields on the ground around the active array and on the bow-tie towers of the inactive array in four-panel mode.
7. Convert the array back to six-panel mode.

A test plan was written (Beauchamp & Hopkins, 1997) and arrangements were made for testing the four-panel mode at Cutler during September 1997. The north array was undergoing extensive repair work to the helix house and painting on all but the three bow-tie area towers. Transmissions were ongoing from the south array. Following the previously prepared test plan, field strength and radiation hazard measurements were made with the south array in six-panel mode. The south array was converted to four-panel mode during a normal Monday down day. Transmitting operations were resumed for 1 week in four-panel mode while radiation hazard and field strength measurements were completed.

The six-panel mode measurements were completed during the week prior to switching to four-panel mode. The radiated power and radiation resistance were determined by an extensive field strength survey during that week. At the same time, radiation hazard measurements took place on the bow-tie towers of the inactive north array (N5, N6 & N7). On tower N5 the tests included radiation hazard measurements involving a cable rigged to simulate a winch such as might normally be used to haul paint and other materials up the tower. Also, a radiation hazard survey was performed in the vicinity of the south-array helix house and under the south array panels.

The north array was switched to four-panel mode during the normal 12-hour downtime on Monday, September 15. Following this conversion, field strengths were measured at a few locations se-

lected from the previous survey to determine the four-panel radiated power, and the radiation hazard measurements were repeated on the north array bow-tie towers and around the south array.

Since the closure of the Annapolis VLF transmitter, the recall time required by SUBLANT for normal Cutler downtime is 30 minutes. However, for this test, arrangements were made to allow a 1- hour recall during the downtime periods scheduled. These included Monday, 15 September; the contingency day on Friday, 18 September; and reconfiguration to normal six-panel mode on Monday, 22 September. The contingency day on Friday had been scheduled to convert to five-panel mode if four-panel mode was not adequate for some reason.

The tests began on Tuesday, September 9. During the first week, six-panel field strength and radiation hazard measurements were completed. The array was converted to four-panel mode on Monday, September 15. Unfortunately, an insulator in panel S3 failed on Tuesday morning, which stopped the testing. The south array went back online late that afternoon in four-panel mode, but with the bow-tie panels activated precluding radiation hazard measurements on the bow-tie towers. Contingency downtime, scheduled on Friday, was used to reconfigure to the originally planned four-panel mode. The weather precluded completion of radiation hazard measurements on the towers until the following Monday morning. Following completion of these measurements, the array was converted back to six-panel mode to allow resumption of normal operation. The insulator failure and required repair effort left no time for five-panel mode measurements, which had been originally planned as a backup if four-panel mode was not adequate. Success of four-panel mode tests made the conduct of five-panel mode tests unnecessary.

This report describes the radiation hazard and field strength survey measurements. The results of the helix house antenna measurements are also reported here. The details of the helix house measurements and the transmitter adjustments and testing are being reported separately.

ANTENNA DESCRIPTION

GENERAL

The U.S. Navy VLF transmitting station at Cutler, Maine is the "flagship" of the U.S. Navy's fixed very-low-frequency (FVLF) transmitting sites. It is located in Washington County, Maine on a peninsula near the small town of Cutler. The Cutler VLF antenna consists of two arrays (north and south). Cutler normally radiates 1-million watts when using both arrays (dual mode) and at times radiates as high as 1.8-million watts. Less power is radiated when using only one array (single mode). In order to radiate power levels of this magnitude in the VLF band, an enormous antenna system is required. Each array consists of 13 towers approximately 900 feet tall. Each array is nearly 1 mile across and together they cover almost the entire peninsula. Considering both arrays, this antenna system is one of the largest in the world. Figure 1 provides an overall top view of the antenna.

Each array is comprised of six diamond-shaped panels that are supported by halyards from the tower tops leading to permanent winches at the bottom of the towers. A single array of this type is termed a TRIDECO antenna (Alberts et al., 1957; Hansen & Watt (unpublished); Watt, 1967; and Woodward, 1961). This antenna is an electrically short top-loaded monopole, as are all the U.S. Navy's VLF antennas. The six diamond-shaped panels comprise the top-load of the antenna. These panels are formed by eight cables or conductors that run out from the antenna center and one heavy support wire (catenary) that runs across the center of the diamond (figure 2). Each panel is fed by a four-wire cage suspended from a truss near the central apex of the panel. These panels are designed to operate at high voltage. The towers and halyards are grounded. The halyards are insulated from the high-voltage panels by insulators located at the end that connects to the panel corner.

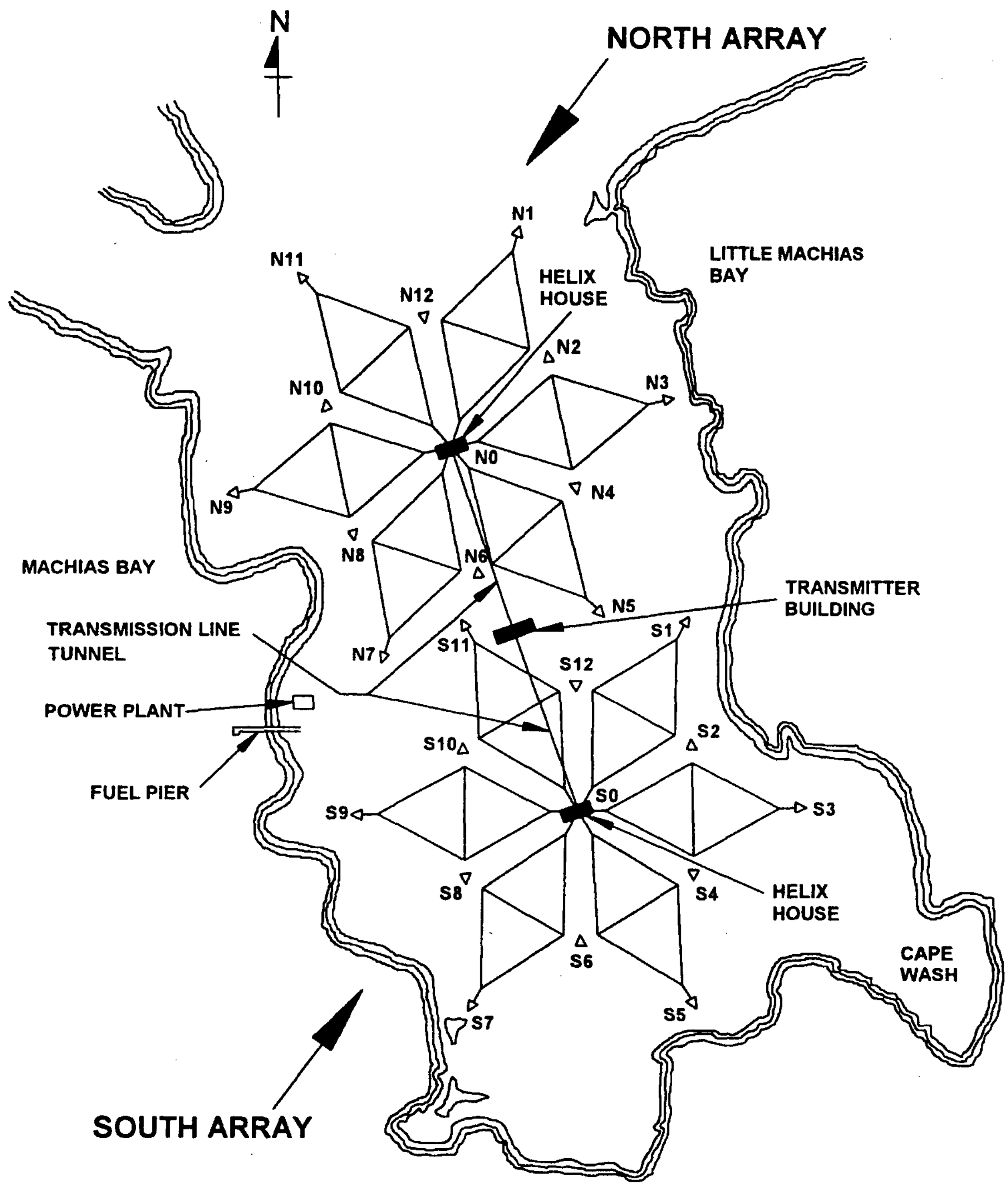

Figure 1. General layout, Cutler Peninsula.

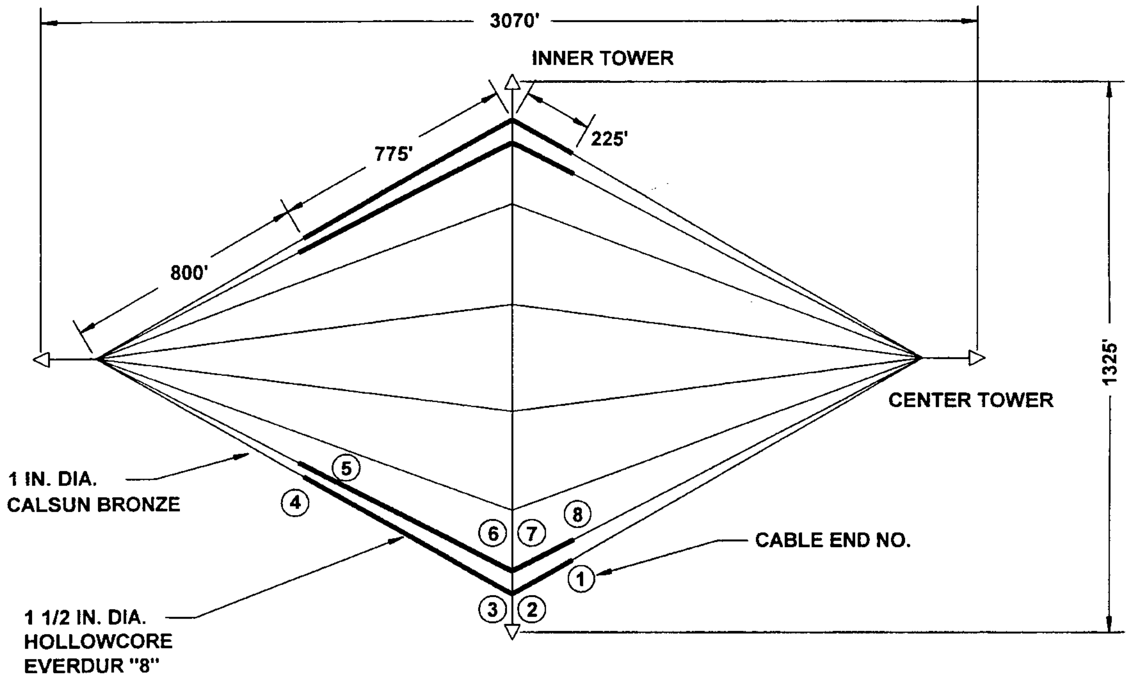

Figure 2. Plan view of a typical panel in VLF antenna array.

TOWER NUMBERING AND HEIGHTS

The two arrays are called north array and south array. The tower numbering is the similar for each array, with the towers of the north array preceded by the letter, N, and the towers in the south array preceded by the letter, S. The six panels of each array are supported by 13 towers. Tower zero (i.e., N0 or S0) is located at the center of each array. There are six odd-numbered towers (N1-N11 or S1-S11) located on a 3070-foot radius circle centered on tower zero. These six towers form the outer ring. Each array also has six even-numbered towers (N2-N12 or S2-S12) located on a 1875-foot radius circle centered on tower zero. These six towers constitute the inner ring. The towers on the inner and outer rings are numbered clockwise when viewed from above. The center towers (N0 and S0) are 979.5 feet tall; the even-numbered inner-ring towers are 875 feet tall; and odd-numbered outer-ring towers are 799 feet tall.

The panels are labeled using the of the tower supporting their outer apex (i.e., N1 or S1, etc.). For example, the outer apex of panel N1 is supported by the halyard from tower N1. The center catenary of panel N1 is supported between towers N12 and N2. The feed-cages are also labeled with letter of the corresponding panel. The inner corner of each panel is supported by tower N0.

TOWER STRUCTURE

The towers are all grounded and supported by grounded guy wires. The top-load panels are hoisted into position by halyards attached to permanent winches located at the tower base. All the halyards, except those on tower zero, lead to the panel through a counterweight suspended on a separate 200-foot tower located next to the tower base. There are two 200-foot counterweight towers next to each inner-ring (even) tower and one 200-foot counterweight tower next to each outer-ring (odd) tower. The counterweight system allows the top-load panels to be lowered automatically when ice accumulates on them. As the panels come down, the counterweights rise up on the counterweight tower. Each counterweight pulley system has a 5 to 1 mechanical advantage so that the panels can be lowered to the ground severe icing occur when the deicing system was not be working, which happened once during construction. The panel corners connected to tower zero are not fed through counterweights and are not lowered during icing conditions.

The halyards were originally insulated from the panels by a string of 16 Lapp compression cone fail-safe insulators with large grading rings on each end. The string plus hardware weighed in excess of 6 tons. During the summer of 1996, the old fail-safe insulator strings in the south array were replaced with a single much smaller and lighter safety core insulator. During the summer of 1997, the insulators in the north array were similarly replaced.

Each panel is fed using a vertical element made up of a four-wire cage, which is known as the down-lead cage. The down-lead cage is suspended from a truss that runs across the diamond-shaped panel apex supported by the central tower. Each wire from the four-wire cage is connected to two of the eight top-load conductors. The down-lead hangs from the truss down to an elevated hinge, where it turns and runs horizontally to the top of the helix house. This section is known as the horizontal feed-cage or feeder. The hinge is kept in position by an insulated halyard connected to a counter-weight (figure 3). As shown in figure 3, the feeder counterweights are suspended from 90-foot towers. The counterweights for two feeders are suspended from the same tower. Thus, there are three 90-foot counterweight towers associated with each array. The combination of the nearly horizontal feed-cage and the down-lead cage with the counterweighted hinge allows the top-load panel to move

a large distance without increasing the structural loading on either the feed-cage or the down-lead. The down-leads and feed-cages are labeled by the same number as the panel they feed.

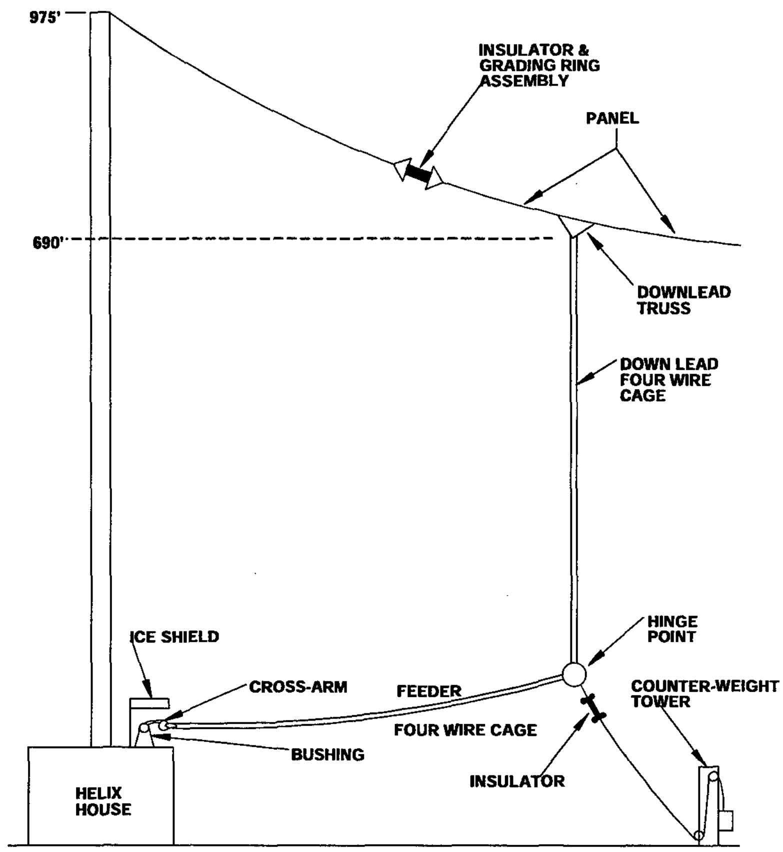

Figure 3. VLF Cutler feed-cage and counterweight configuration.

The antenna tuning and matching elements are located in a large building, known as the helix house, which is adjacent to the base of the center tower of each array. Each helix house has two large galleries extending from the main part of the building, which partially surrounds the central tower base. There are three large special feed-through bushings, one on the top of the main building and one on top of the end of each gallery. Above each bushing is a large steel structure that provides protection from falling ice and a pulloff structure to support the feed-cages.

Two panels are connected to each bushing. The four wires from the feed-cages of two panels are brought to an insulated crosspiece known as the crossarm. The cross-arm is made from approximately 12-inch aluminum pipe with 45° sections at each end. The ends of the 45° sections are covered with hemispheres. The crossarm is suspended between the ice shield and helix house roof by insulators. From the crossarm, there are five cables connecting to the top of the bushing.

Each array consists of three divisions defined by the three individual bushings and the panel pairs connected to them. The south array contains divisions one through three, consisting of panels (11 and

1), (3 and 5), and (7 and 9), respectively. The north array contains divisions four through six, consisting of panels (5 and 7), (9 and 11), and (1 and 3), respectively. Note that the bow-tie panels in the south array consist of division 1 and that in the north array they consist of division 4.

The top of the tuning coil (helix) is directly connected to each of the three bushings. The antenna current exits the helix house through these three feed-through bushings, and is conducted to the top-load via the feed-cages and down-leads. The antenna can be thought of as consisting of all six top-load panels fed in parallel.

The top-load panels can be lowered to the ground to perform maintenance. The outer three corners of a panel can be lowered to the ground for inspection and maintenance in approximately 1 hour. Lowering the inner (tower zero) corner takes considerably longer due to the care necessary to protect the feed-cage, down-lead, and truss from damage.

TOWER DESCRIPTION

All the towers have a triangular cross section when viewed from above. The faces are numbered zero, one, and two. The zero face is always perpendicular to a radial from tower zero. The numbers increase clockwise as viewed from above. The tower legs are numbered corresponding to the opposing face.

All the towers have four guy levels. They have rest platforms located approximately every 80 feet, with ladders located inside the tower between rest platforms. The rest platforms have safety railings. The tower faces have cross struts in the shape of an X. There are winch houses near the tower base for the support halyards. One halyard leads from each winch house to a 200-foot counterweight tower and from there to a sheave on the top of the tower.

The tower top extends above the top guy as the top guy wires attach to the tower just below the tower top at the base of the sheave platform (figure 4). The sheave platform of the inner and outer towers is very similar except that the inner towers have two sheaves and no beacon.

Inner Towers

The inner (even-numbered) towers support one corner of each of two of the diamond-shaped panels. The heavy support cable between two inner towers is known as the support catenary.

The inner towers are placed such that the zero face is on the side away from tower zero (figure 5). The inner towers support one corner of two panels and, therefore, have two winches and counterweight towers next to the base. The support cable (halyard) for each panel runs up the outside of the tower in the center of faces two and three. The halyard run up the tower face starts from the top of the counterweight tower at 200 feet elevation and a distance of approximately 75 feet from the tower face. It goes to the sheave located on the tower top. The distance from the halyard to the tower face decreases as it goes up the tower, closely approaching the tower at the entrance to the sheave.

The section at the top of the tower, known as the sheave landing platform (figure 4), is where the halyard sheaves are located. The sheaves extend out from the center of sides one and two. The even-numbered towers do not have a beacon on the top. Measurements were done on the platform and at several locations outside the tower, where access is required for normal maintenance, including on top of the tower.

Outer Towers

The outer (odd-numbered) towers are shorter than the inner towers, but are configured similarly. These towers support the outer corner of one of the diamond-shaped panels.

The outer towers are placed such that the zero face is on the side towards tower zero so that the single sheave at the top of an outer tower is pointing at tower zero (figure 6). The outer towers have a sheave platform similar to the inner towers but with only a single halyard with corresponding winch and top sheave. The winch connects to the halyard that goes up the zero face. Note that the configuration of the outer tower top is the same as shown in figure 4 except that there is a hazard light located at the center of the tower top.

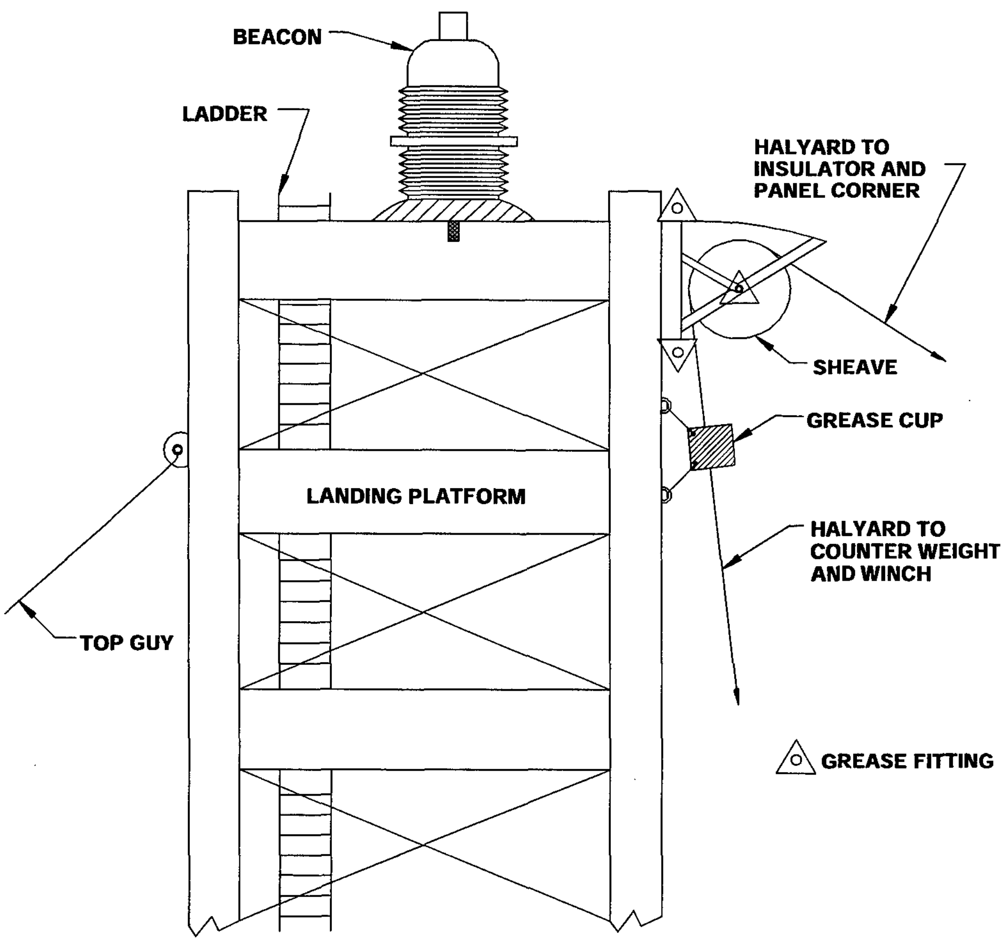

Figure 4. Tower top configuration.

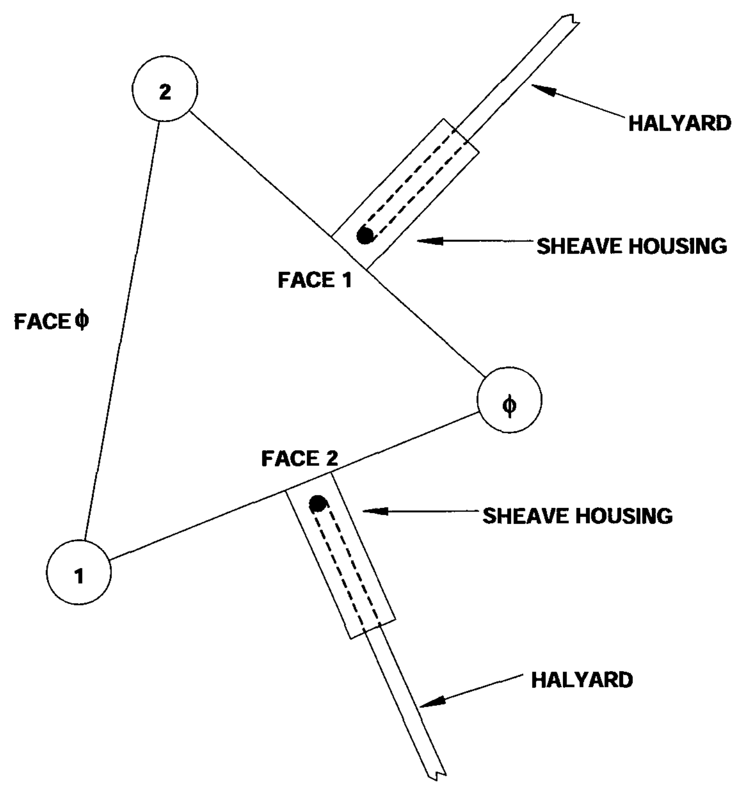

Figure 5. Top view inner (even-numbered) tower.

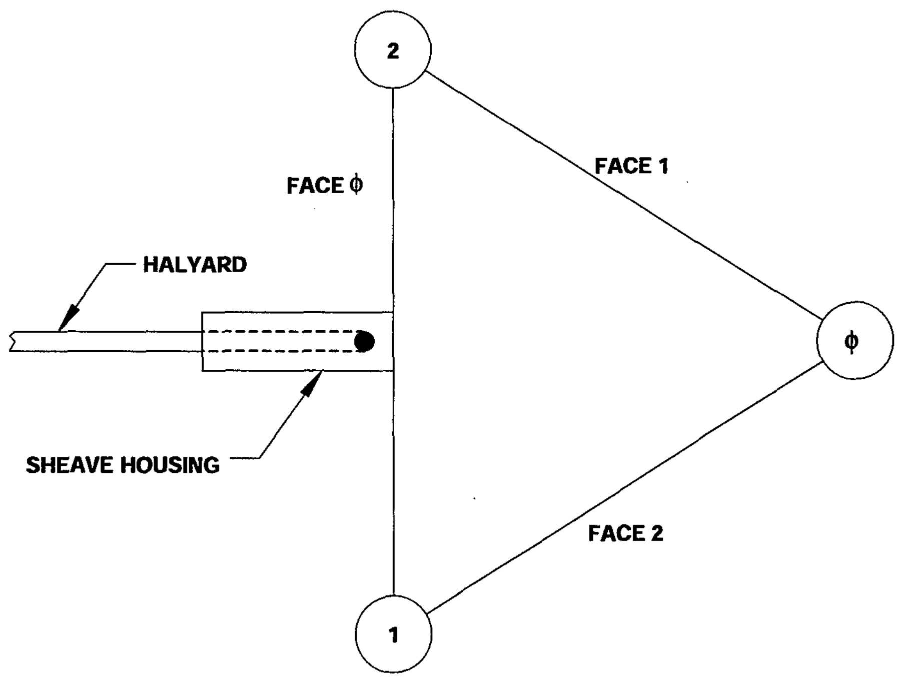

Figure 6. Top view of outer (odd-numbered) tower.

Helix House

The antenna is tuned and matched by a set of high-Q, air-wound inductors and variometers located in the helix house. The primary tuning is done by a huge air-core inductor known as the helix. The windings of the helix are made with three pieces of 4-inch diameter litz wire in parallel. The top of the helix is connected to each of the three feed-through bushings. The connection to the bushing on the main part of the helix house is made directly using two pieces of the 4-inch litz wire in parallel. The connection to the bushings on the end of the two galleries is made using a large (8-inch diameter) copper bus.

The helix has several taps that can be changed manually to provide coarse changes to the antenna tuning circuit. It is usually only necessary to change taps when changing frequency. Variable tuning to compensate for environmental changes is performed by a large air-core variometer, which is also wound with three pieces of 4-inch litz wire in parallel. This tuning variometer is in series with the helix inductor in the antenna circuit.

In each helix house there is a large ferrite core inductor known as a saturable core reactor. The inductance of this reactor can be rapidly varied electronically over a finite range of values. The reactor can be connected in parallel with a portion of the helix and/or the tuning variometer. It is used to tune the antenna in synchronism with the two frequencies of the minimum shift keying (MSK) modulation. The MSK waveform consists of two frequencies selected to transmit marks and spaces. The reactor driver receives an antenna tune signal from the modulator, which enables it to tune the antenna synchronously with the mark and space frequencies.

The saturable core reactor provides a method of increasing the effective bandwidth of the antenna (bandwidth enhancement). When the reactor is operating, it resonates the antenna circuit at both the mark and space frequency, and the impedance reflected to the transmitter is nearly pure resistance. This reduces the stresses on the transmitter, transmission line, and matching components. These stresses are greater for larger values of Q, which occur at lower frequencies for Cutler. In fact, the reactor is necessary to radiate full power at the lower frequencies at Cutler. For six-panel operation on 24.0 kHz, the reactor is not necessary to radiate full power. However, for four-panel operation, the antenna bandwidth is reduced and the reactor is needed. The voltage on the reactor depends upon its helix tap connections. In four-panel operation, the helix taps must be changed to keep from exceeding the reactor voltage limits.

A coupling variometer converts the series resonant antenna to a parallel resonant impedance and to change the impedance at mark and space frequencies to match the transmission line impedance of 100 ohms. This coupling variometer, known as the triple deck, consists of three single variometers in parallel, each wound with 4-inch diameter litz wire. The coupling variometer is connected from the tuning variometer to ground. The 100-ohm transmission line from the transmitter building is also connected to the top of the coupling variometer.

TRANSMITTER

The transmitter is located in a building approximately halfway between the center of each array (figure 1). The transmission line and other cables for power, monitoring, and control are routed to each helix house through a tunnel large enough to walk through.

DEICING SYSTEM

Purpose

Cutler is on the coast of Maine, an area that often has periods of heavy icing during the late fall and early spring. Each array was designed to be connected to a 60-Hz power source to heat the antenna conductors, thereby melting the ice. The array cannot transmit while deicing is in progress. The reason for having two arrays was to allow continuous operation during periods of icing by alternately deicing one array while transmitting on the other.

Connection

When connected for deicing, the conductors of the top-load become a giant three-phase load. Each division, consisting of the bushing and two associated panels, form one leg of that load. A large motorized knife switch with two arms that swing out from the helix house wall connects the deicing power to contacts on either side at the bottom of the bushing. There is also a large motorized ground switch that grounds the center conductor of the bushing. This is used for the safety ground when the antenna is not in use, as well as the ground for the deicing circuit.

The four wires in the feeder and down-lead cage are insulated from each other with small insulators designed to withstand the voltage developed during deicing by the 60-Hz current. This voltage is much less than the RF voltages developed when transmitting. The bushing has an internal switch activated by air pressure that switches between transmit mode and deice mode. A simplified schematic of the deicing mode connection is shown in figure 7. Each wire of the four-wire cage connects to two top-load conductors. The panel also has small 60-Hz deicing insulators placed to

isolate these wire pairs to form a series circuit. In the figure, panel wire pairs are represented by a single line.

The four-wire feed-cages from two panels for a total of eight individual cables come to the insulated cross-arm, suspended above the bushing. Figure 7 shows that these are connected. Only five cables connect from the cross-arm to the bushing. Four of these go to the insulated connections on top of the bushing. These cables are insulated from the crossarm by the small 60-Hz insulators. The fifth connection, known as "deice ground," is electrically connected to crossarm and goes to the bushing rain shield. One cable from each is connected to the crossarm. The main feed-through conductor of the bushing is connected directly to the rain shield. When in deice mode, the ground switch inside the helix house provides the ground connection for deice ground.

All of the deicing current flows in each wire of the four-wire down-lead and feed-cages. However, only half of the deicing current flows in each of the top-load conductors. Both of these conductors are nominally 1 inch in diameter.

Deicing Current

The deicing system was designed to develop 1.63 watts per square inch of conductor based on the original specification. At 60 Hz, the nominal current required to dissipate this power in the 1-inch diameter copper feed-cage and down-lead cables is 1938 amps. Each top-load conductor carries half the current of the down-lead cage cables. They are also 1 inch in diameter, and must have four times the resistance of the copper cables, to dissipate the same amount of power. This is the reason that the top-load conductors are made from a special alloy known as Calsun Bronze, which has approximately four times the resistance of copper.

There are sections of the outer two top-load conductors at the panel corners supported from the even-numbered towers that are 1.5 inches in diameter. This diameter was required to keep these conductors from going into corona when operating at the lower frequencies. These sections have 1.5 times the surface area and in order to provide the same power dissipation density for deicing, they need 1.5 times the resistance of the 1-inch diameter top-load conductors. This was accomplished by using a special cable partially hollow inside, known as a hollow core. There has been some trouble with the hollow core breaking strands near the ends, apparently due to wind induced vibration (Hansen, 1994).

Power

The nominal design goal of 1.63 watts per square inch amounts to a little more than 1 megawatt per panel, or about 7.5 megawatts for the entire array. VLF Cutler has its own power generation facility capable of generating up to 18 megawatts. The station has always been powered by this facility. The large amounts of power required for deicing are supplied by the power station. During the design, there was uncertainty as to the amount of power required for deicing, and excess power generation capability was provided. The system can supply up to 12 megawatts for deicing one array, as well as providing the power required for transmitting from the other array.

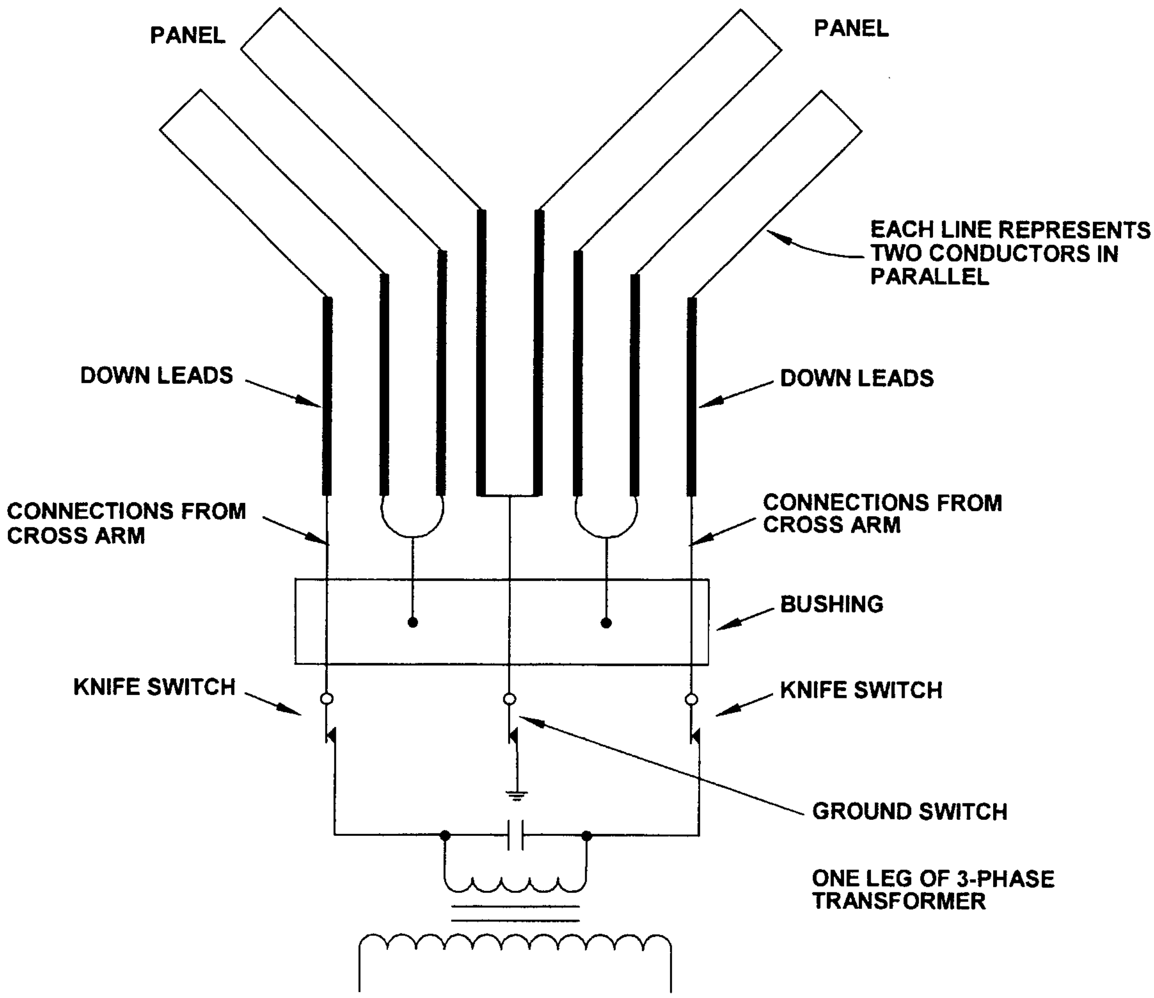

Figure 7. Simplified schematic diagram of one division in deicing mode.

Transmitting

Transmitting is accommodated by disconnecting the deicing power knife switch and the ground switch. The air-activated switch in the bushing operates to connect all the five wires coming to bushing in parallel. Figure 8 provides a simplified schematic of the transmitting configuration. This connection allows all the conductors in both feed-cages to transmit at the same RF potential.

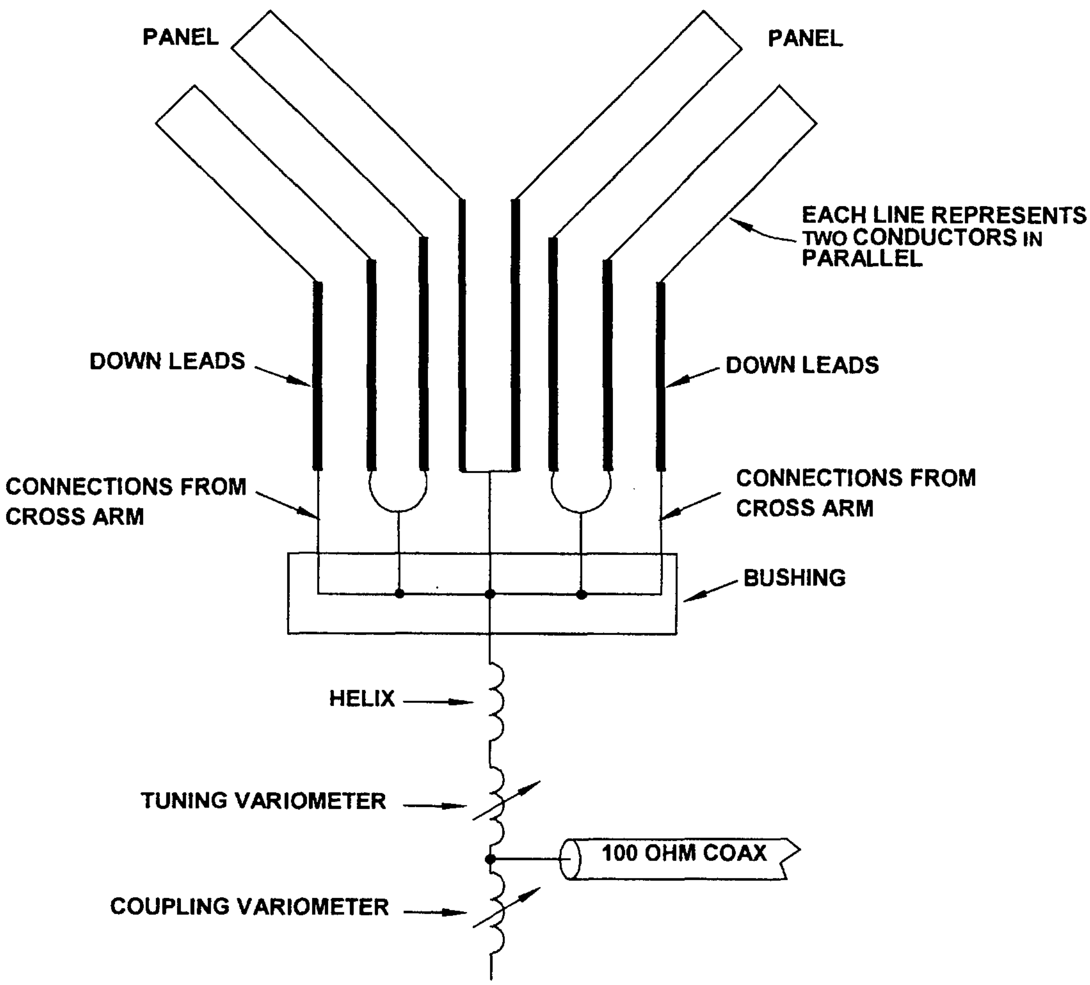

Figure 8. Simplified schematic diagram of one division in transmit mode.

MAINTENANCE PROCEDURES

One of the test objectives was to determine those maintenance procedures that could be safely performed on the down array while transmitting on the other array. The existing station policy at the time of these tests does not allow access to the bow-tie area towers while the other array is operating. Thus, normal maintenance on the bow-tie towers of either array requires total downtime. It is desirable to eliminate this requirement, if possible. For this reason, we made radiation hazard measurements involving personnel in position to simulate performance of normal maintenance procedures. These procedures are described below.

Routine

The maintenance procedures routinely performed on towers are described below.

Light Bulb Replacement. There are two types of lights on the towers. They are called hazard lights and beacons. The hazard lights are small light fixtures mounted on the tower legs and located outside

the tower. There are four levels of these lights on the odd-numbered outside towers. All of these lights are located at a rest platform. In order to change the bulb, the mechanic sits on the rest platform straddling the tower leg and reaches around the tower leg with both hands to lift the glass enclosure and access the bulb for changing. This is illustrated in figure 9.

There are also three beacon lights located on the outside towers. These lights are located at two different elevations positioned at the center of a rest platform and the third one is located on the tower top. The beacons are larger than the hazard lights, consisting of a fixture about 2.5 feet tall. This fixture contains a top-half and bottom-half, each containing a large high-power bulb and having a Fresnel lens to focus the light towards the horizon. The top of the fixture has a metal cap that is electrically connected to the tower. The fixture has a hinge in the middle and the top-half can be tilted open allowing access to the interior for changing the bulbs. To change the bulbs on the tower top beacon, the antenna mechanic sits on the top crossbeam next to the beacon, opens the beacon and replaces the bulbs (figure 9).

Greasing Tower Top Sheave Assembly. The sheave that feeds the halyard out to support the top-load panel is located just outside the landing or sheave platform, just below the tower top (figure 4). This sheave is supported by a vertical bearing that is located just outside the plane of the tower face. The top-load panels have a large wind cross section and move around some, depending upon wind velocity. The vertical bearing allows the sheaves to swing right or left to keep them perfectly aligned with the direction of the support cable attached to the panel.

Each sheave fixture has four grease fittings. There is one on either side to enable greasing both of the main sheave bearings and there is one each located on the top and bottom of the vertical bearing just outside of the tower face. The greasing is done using a hand-pumped grease gun with a long rubber hose with a metal fitting on the end matching the sheave grease fittings. One antenna mechanic stays inside on the landing platform and operates the grease gun, while another antenna mechanic climbs outside the tower in a position to connect and hold the hose onto the grease fitting.

For the two bearings on the side of the sheave, the mechanic is outside the tower face, hanging onto the frame that supports the sheave with one hand while holding the hose onto the grease fitting with the other hand. For the grease fitting on the top of the vertical bearing, the mechanic is outside of the tower on the top, laying on his stomach across the tower top frame, reaching down to hold the hose onto the grease fitting. For the grease fitting on the bottom of the vertical bearing, the mechanic remains inside the tower.

The grease gun and grease required for this procedure are hand-carried up the tower by the antenna mechanics who will be performing the procedure.

Halyard Cable Greasing. A portion of the steel cable used for the halyard is continuously exposed to the air when the panel is in its normal elevated position. This portion of the cable is coated with grease periodically to prevent it from corroding.

Hoisting Materials. The grease gun and buckets of grease needed for this procedure are hoisted up to the tower top by a unique method using the halyard winch. The materials are first hoisted by hand to the top of the counterweight associated with the halyard to be greased. There the materials are tied onto the halyard using light line in such a way that they hang several feet below the tie point. The

halyard winch is then let out, lowering that corner of the panel.

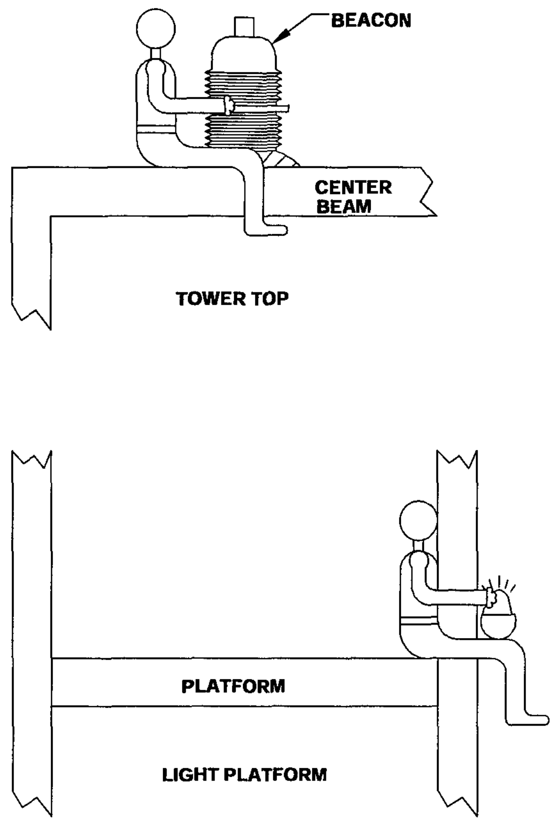

Figure 9. Tower hazard and beacon, light bulb replacement.

As the panel lowers, the halyard carries the materials up the tower. The winch is stopped when the materials reach the height of the rest platform just before the landing platform. A nonconducting rod is used to reach out, hook the materials, and bring them into the rest platform. From there they are hoisted by hand up to the landing platform. The halyard is then let out all the way until the insulator lands on the ground. At that time, inspection and maintenance procedures are carried out on the insulator and associated hardware. When completed, the insulator is hoisted back into position while at the same time greasing the halyard (see below).

Greasing the Halyard. The technique for greasing the cable consists of placing a special clamp-on greasing mechanism (grease cup) around the halyard at a location just below the point where it enters into the sheave (figure 4). This is done with the halyard let completely out so that the insulator is on the ground. In order to attach the grease cup, the antenna mechanic climbs outside of the tower under the sheave. The grease cup is held in position using light line. The grease gun is located inside of the tower on the landing platform and is attached to the grease cup by the long rubber hose. The cable is pulled through the grease cup by raising the panel corner with the halyard winch. The grease cup is pressurized as the cable runs through it by use of the hand-pumped grease gun. Using this method, the entire exposed portion of the halyard cable is coated with grease.

Counterweight Towers. There are sheaves on the counterweight and the top of the counterweight towers that need to be greased periodically.

Tower Inspection. The towers are usually inspected every 2 years. For inspection, the tower is accessed everywhere, both inside and outside. Cameras are carried to take pictures for documentation as well as telescopes and binoculars for viewing guy wires, insulators, and panel cables. This job is normally contracted out. However, the on-site antenna mechanics always escort the inspectors carrying equipment, etc.

Special Projects

The Cutler arrays have been in place since the early 1960s and they will probably be required for the foreseeable future. In order to maintain the structure without deterioration, periodic special projects are required. At Cutler, these are usually, but not always, contracted out. Past special projects have included guy replacement and tower painting. Recently, special projects have been done to repair the roofs of both helix houses and to replace all the halyard insulators in both arrays. Guy tensioning and bushing repair are normally performed by the on-site antenna mechanics. The towers also require periodic painting and a special painting project was going on during the test period and is described in the following paragraphs.

Tower Painting. This job has always been contracted out. Previous tower painting projects put new paint over the existing paint by hand with brushes or mittens. Before painting, the surfaces to be painted were prepared by sanding, scraping, and wire brushing to remove loose paint. The contractors for these projects probably used a light winch rigged on the towers to hoist materials; however, no other major rigging was used. The bow-tie area towers were only painted during the Monday downtime and, therefore, no extra downtime was required. Because of the simple method used for painting the towers, it was not necessary to leave any rigging outside of the bow-tie towers between the times when they were painted.

There was a painting project going on at Cutler during the test period. This painting project requires the paint to be cleaned completely off the tower by water-blasting. The water used must be collected to keep the lead-based paint from being spread in the environment. After cleaning the towers are spray-painted. The area of the tower being be sprayed is covered to keep overspray to a minimum.

During the summer/fall seasons of 1997, the contractor worked on eight towers of the north array, none of them in the bow-tie area. These towers were at various stages of completion during our test period and we examined the rigging on several of them as best we could from the ground. The major feature of the painting rig is a platform that goes completely around the outside of the tower and that can be moved up and down the tower. We could not determine the method of movement or suspension of this platform, but it probably takes multiple winches.

It appears that the towers are completely water-blasted before being spray-painted. The water-blasting appeared to start at the tower bottom. As a section was completed, the platform was then hoisted up to the next section. When the tower has been completely water-blasted, the platform is at the top, where spray-painting begins. Similarly, the platform is lowered as each section is painted, til the tower is completed and the platform is again at the bottom.

The tower section immediately above the platform is covered with a tarp starting at the floor of the platform and going up vertically. This keeps paint spray from drifting out into the environment. For

water-blasting, it is assumed that in addition to the vertical covering, some kind of catchment is used and the collected water is drained down to the tower bottom for disposal.

Several towers in the north array were examined. These towers were at various stages of completion of the painting project. Most of these towers had several things hanging off them at several places. There were some towers with two winches rigged. The one winch operation that was observed used two winches mounted on trucks. One winch was used for the hoist and the other operated the tag line. The hoist winch was set up a considerable distance from the tower in one direction and the tag line winch was in a different direction from the tower. Both winches had operators.

What appeared to be the high-pressure pump for the water-blast system was set up near the tower base and the water was fed up the tower using a high-pressure rubber hose. On one tower, this hose was observed to be hanging well outside of the platform area.

Station Operating Procedure for Tower Access When Transmitting

Cutler operated for many years on a frequency of 17.8 kHz, but changed to 24.0 kHz a few years ago. The voltage and current for operation on 17.8 kHz is approximately 80 percent higher than for operation on 24.0 kHz. During 1983, while operating on 17.8 kHz there was a radiation hazard survey conducted on the ground, on top of the helix house and apparently on the towers (Hagaman, 1983). There may have been a radiation hazard survey on the towers following the change to 24.0 kHz, but the report is unavailable. Apparently, based on those measurements, the station developed their policy for access to the towers while transmitting, which is described as follows:

1. With one or both arrays active, personnel cannot climb or work on:
   a. Tower zero of the active array
   b. 90-foot counterweight towers of active array
   c. Even and odd towers in active array above 200 feet
   d. Bow-tie area towers of an inactive array above 200 feet
   e. The helix house roof of an active array
2. With one or both arrays active, personnel can climb and work on:
   a. All towers of inactive array except bow-tie area towers above 200 feet
   b. All counterweight towers of inactive array
   c. All towers of active array up to 200 feet except tower zero
   d. All counterweight towers of active array except the 90-foot towers
   e. The helix house roof of the inactive array

In addition, the mechanics are allowed to raise and lower any panel of the inactive array. However, they are not allowed to disconnect or disassemble any part of the bow-tie panels. Care must be taken when raising and lowering the bow-tie panels during dry conditions, as sparking between the panel and ground can start grass fires.

Under this policy, total downtime is required to perform routine maintenance, painting, or special projects on the bow-tie area towers of either array.

There was a ground-based radiation hazard study done in 1992 by NAVELEX Charleston (Charlow, 1992). The summary of this report includes the statement that "no potential personnel hazards (from EM fields) exist at the VLF site." This report also recommends that the station "continue to observe the standing operating procedures governing maintenance, especially restrictions on climbing towers or rigging operations during transmitter operations."

FOUR-PANEL CONFIGURATION

HELIX HOUSE

In order to keep the reactor voltage within limits in four-panel operation, the helix taps had to be changed. In the past, these taps were changed by putting up a scaffold in the helix house and manually installing the jumpers. This procedure, including the setup and takedown time for the scaffolding, takes approximately two normal workdays. This is an unacceptably long downtime for conversion to four-panel mode. The station antenna maintenance personnel worked out a tap change procedure that did not require scaffolding. This procedure takes somewhat more than 1 hour to complete. It was determined that the 1-hour recall requirement could be met no matter when the recall came by either continuing on to four-panel mode or reverting to six-panel mode.

PANEL GROUNDING

In order to ground the panels as required in four-panel operation, it is necessary to disconnect them from the bushing. When one array is deactivated and grounded, the ground connection is at the bottom of the bushing inside of the helix house. When the other array is active, considerable RF current flows to ground through the bushing, especially from bow-tie panels. Consequently, making or breaking the connections on the top of the bushing while transmitting on the other array can result in serious shock hazard. Therefore, station operating procedures require that that connection or disconnection of the leads on the top of the bushing only occur when both arrays are inactive.

Even with no nearby transmitters on the air, an ungrounded panel can be dangerous, due to static charge buildup. Therefore, even when the other array is inactive, the cables, being disconnected from the bushing top, must always be connected to ground by a separate cable, a safety ground, prior to disconnecting them from the bushing. Since all the cables of a division are electrically connected, grounding one of them is sufficient during the disconnection or connection process. This process should not be done when there is a thunderstorm anywhere in the area (i.e., if thunder can be heard).

South Array

Grounding Technique. The south array bow-tie panels are S11 and S1 and were grounded for this test. These panels are both in division one and are both connected to the bushing on the main part of the helix house.

Grounding two panels in the same division is simple, amounting to first connecting them to ground with a grounding cable, then disconnecting all five cables at the bushing, tying them together and holding them well away from the bushing using light line (figure 10). The station has special copper cables with multiple clamps attached near one end for attaching to the cables and a single clamp at the other end for attaching to ground. For the disconnection/connection process, one of these cables was used as a safety ground with the ground end connected to one of the crossarm support turnbuckles nearby.

The main ground connection used during four-panel operation was made using three 1/2-inch diameter copper cables strung from the base of the helix house to the roof. Each of these copper cables was connected to three ground wires exposed at the base of the helix house using clamps (figure 11). On the roof, two of the special ground cables with clamps were used to connect the five cables disconnected from the top of the bushing to the three copper cables, all run in parallel.

Given that the copper cables and special grounding cables are in place and ready to be connected, the entire process of grounding one division can be accomplished in about 1/2 hour with both arrays inactive.

Figure 10. Four-panel mode grounding configuration on helix house roof.

Figure 11. Four-panel mode grounding configurtion at base of helix house.

Ground Currents. Following reconfiguration of the antenna to four-panel mode, the currents in the three ground wires were measured. The current flowing in these grounded wires is out of phase with the current in the active down-leads and subtracts from the total antenna current moment (i.e., effective height). The ratio of the "down" current, flowing from the grounded panels, to the "up" current flowing to the active panels was 7.26 percent. To first order, this is the reduction in the effective height expected due to operation in four-panel mode rather than in six-panel mode.

North Array

The north array panels N5 and N7 are the ones to be grounded to reduce the fields on the south array bow-tie towers. These two panels are in the same division (division five) and both are connected to the bushing on the main part of the helix house. Thus, the grounding technique to be used on the north array is the same as described above for the south array.

OTHER CONFIGURATIONS

Other configurations that might be considered are five-panel mode or a four-panel mode with one panel in each of two divisions grounded. Both of these configurations require one panel in a division to be active, while the other panel is grounded. For this case, the crossarm is at radio-frequency high voltage and all cables connected to the grounded panel must be removed from the vicinity of the crossarm. Probably, the best way to do this would be to disconnect the feeder for the panel to be grounded and lower it to the ground. Depending upon which of the two panels is selected for grounding, the deicing ground connection from the crossarm to the bushing rain shield may require a separate cable.

These configurations are much more complicated, require considerably more total downtime to rig and are not needed for work in the bow-tie area. These configurations are not necessary on 24.0 kHz except for some unforeseen event. These configurations should not be attempted by station forces without further engineering support.

ANTENNA MEASUREMENTS

EFFECTIVE HEIGHT

In order to determine the effective height of the south array at Cutler in both six-panel and four-panel mode, an extensive field-strength survey was made, while at the same time measuring the antenna current. From the knowledge of the antenna effective height, the radiation resistance and radiated power of the antenna can be determined. This measurement is important for determining antenna radiation efficiency and the radiated power needed for coverage predictions.

These measurements are described in appendix A along with a brief description of theory and technique. A more complete discussion of this type of measurement is contained in Hansen (1994). A partial history of effective height measurements at Cutler is given in the appendix. Note, the results of the extensive effective height measurement on 24.0 kHz, reported here, gave almost exactly the same result as a much less comprehensive measurement done by SSC SAN DIEGO* (Hansen, 1983).

IMPEDANCE

Measurement of the antenna impedance parameters were taken at low power using a network analyzer and special Pacific Sierra Research (PSR) impedance probe (Hansen & Gish, 1995). Antenna system gross resistance and bandwidth were measured by connecting the probe between the bottom of the antenna tuning elements and ground. Antenna self-resonance and static capacitance were measured using the network analyzer with the probe connected directly to the antenna and with the helix disconnected.

Experience has shown that the resistance measured at low power is usually slightly higher than when measured at high power. This is attributed to moisture that collects on the antenna insulators and, in effect, added shunt resistance. The transmitter has enough power to dry the insulators, thereby reducing the antenna resistance caused by the moisture on the insulators. It has become our practice to measure the antenna resistance at power using the transmitter whenever possible. When available, this is the resistance value reported. The impedance measurements, including the antenna gross resistance at power, are described in appendix A.

SUMMARY

During the test period, antenna measurements were made on the south array in both six-panel and four-panel mode. The measurements are summarized in table ES-1 presented in the executive summary.

Comparison of the measurement results given in table ES-1 shows that grounding the two panels of one array results in a reduction in effective height and static capacitance and an increase in loss resistance. This causes both bandwidth and efficiency to decrease and base reactance to increase, with a corresponding increase in the voltage and current required to radiate a given amount of power.

The measured effective height for four-panel mode was 6.90% less than that for six-panel mode. This corresponds closely to the percentage of the total antenna current that was measured in the ground leads of the two deactivated panels (7.26%) in four-panel mode.

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* formerly Naval Ocean Systems Center (NOSC)

Radiation resistance decreased while the loss resistance increased in four-panel mode over that in six-panel mode. The gross resistance in four-panel mode increased slightly over that in six-panel mode, because the losses went up more than the radiation resistance went down. The net effect is that four-panel radiation efficiency is 10 percentage points less than in six-panel mode.

The static capacitance in four-panel mode was 73% of that for six-panel mode. This decreases the antenna bandwidth.

The self-resonant frequency remains unchanged when operation is changed between four-panel and six-panel mode. This is as expected since the antenna consists of the parallel combination of the six top-load panels and down-leads. Each individual panel and down-lead combination have essentially the same self-resonant frequency. Thus, the resonant frequency is independent of the number of panels that are operated in parallel.

The reduced effective height in four-panel mode requires more current to radiate the same amount of power than it requires in six-panel mode. The radiated power in six-panel mode is 679 kW for 1850 amps antenna current, while to radiate this much power in four-panel mode requires an antenna current of 1984 amps.

The base reactance for four-panel mode is 42% greater than for six-panel mode. For the same antenna current, the base voltage is also increased by this percentage. The base operating voltage for normal operation in six-panel mode is 65.2 kV rms, while to radiate the same power in four-panel mode, the base operating voltage is 99.6 kV rms. This voltage is well below the Cutler design operating limit of 250 kV rms.

In four-panel mode, without the reactor, the power was limited by arcing in the copper room, to 1750 Amps antenna current, corresponding to 523 kW radiated.

In four-panel mode, with the reactor, the highest current level tested was 1981 amps. This corresponds to 670 kW radiated, essentially the same power normally radiated in six-panel mode. With the reactor operating, there was no limitation at 1981 amps and greater radiated power can be achieved. Normally, maximum power would have been determined. However, caution, as a result of the insulator failure, was the main reason that maximum power was not determined. Also, higher power was not required to meet the test objective, which was to radiate the same amount of power in four-panel mode as in the normal six-panel mode.

RADIATION HAZARD MEASUREMENTS

ANSI STANDARD

The Navy has adopted the IEEE/ANSI standard C95.1-1991 [ANSI] as the standard for assessing the Hazard from Electromagnetic Radiation to Personnel (HERP), sometimes called Radiation Hazard (RADHAZ). It is important to note that this standard, like most safety standards, has a considerable safety margin. The ANSI standard is primarily based on the Specific Absorption Rate (SAR), the rate at which the human body absorbs energy from the electromagnetic fields. At lower frequencies, the human body absorbs relatively less energy than at higher frequencies; therefore, based strictly on SAR, exposure to higher fields can be allowed. However, other considerations come into play to prevent allowing arbitrarily high exposure to low-frequency fields. Lower frequencies penetrate more deeply into the body and cause RF currents to flow in the limbs as if they were conductors. Locally high currents in the human body produce tissue heating that must be limited to prevent tissue damage.

For frequencies in the kilohertz range, the effect of tissue heating is overtaken by an effect akin to the electrical shock sometimes experienced in one's home from the 60-Hz power. Below 100 kHz, both nerve and muscle tissue can be stimulated in this way and the local current density is the most useful measure for exposure. For inadvertent (small area) skin contact, such as a fingertip or an elbow, workers near high-power VLF/LF transmitters sometimes experience small shocks called "nuisance shocks," similar to the shocks sometimes experienced when touching a door knob in a dry climate. In general, "nuisance shocks" are not hazardous in occupational settings if workers follow appropriate procedures. Such procedures have proved to be effective in protecting personnel working around these high-power transmitters for more than 30 years.

Human exposure in the VLF/LF spectrum first came under IEEE/ANSI control with the 1991 revision when the 3 to 100-kHz band was included. There were no SAR measurements available for the newly controlled low frequencies and a somewhat arbitrary maximum permissible exposure limit (MPE) was set that appeared to be a linear extension of the 100-kHz values in the 1982 revision. Recently, preliminary SAR measurements in the VLF range were taken at the Navy's High Voltage Test Facility (HVTF) that indicate that the standard for electric field exposure could be increased considerably (Olsen et al., 1997)

The standard is different depending upon whether the area is "controlled" or "uncontrolled." A controlled area is one in which individuals have been warned about the possibility of nuisance shocks and have received training and equipment such as gloves and insulated shoes sufficient to virtually eliminate the risk of serious shocks. An uncontrolled area is where people have access who have not been warned of the exposure in any way. In uncontrolled areas, the standard allows the same E and H field intensities but limits the body currents to much lower values than in a controlled area. At Cutler, the entire VLF transmitting area is gate-controlled and is considered a "controlled area."

For controlled areas in the frequency range from 3 to 100 kHz, the MPE limits are given below. Note that exposure is not allowed if any one or more of these limits is exceeded.

E-field:	614 V/m rms
H-field:	163 A/m rms

Induced currents: 1000*f Amps rms (f in MHz) through each foot or arm; i.e., 24 mA rms at 24.0 kHz (Cutler freq.).

Typically in the vicinity of high-power VLF/LF transmitting antennas, there are regions where the electrical fields exceed 614 V/m. Fortunately, the standard provides a very important "Exclusion" for the low frequencies that allows the above MPE limits to be exceeded if it can be shown that the maximum rms current density, as averaged over any one square cm area of tissue and 1 second, does not exceed 35*f mA/sq. cm, where f is the frequency of the radiated signal in MHz. For a frequency of 24.0 kHz, the maximum current density would be 35 x 0.024 = 0.84 mA/sq. cm. The body current becomes concentrated in the wrists and ankles of workers near VLF transmitters and the current density in these body regions becomes the critical limiting factor under the exclusion. As will be shown below, due to this Exclusion, a sufficient margin of safety exists to permit normal operations in the vicinity of a VLF/LF transmitting antenna.

Under this Exclusion, the following examples are provided: a typical adult wrist has an area of 25 to 35 sq. cm; this area times the limiting current density gives a maximum allowable wrist current at 24.0 kHz of 21 to 29 mA. This range brackets the normal MPE for current and is easily kept under control with the use of good-quality gloves. For the ankle, a typical adult ankle has an area of 50 to over 60 sq. cm; this area times the limiting current density gives a maximum allowable ankle current of 42 to over 50 mA. This range is considerably higher than the MPE for current and would not be expected except for E-field exposures in excess of 10 kV/m. Access to areas with fields of that magnitude are effectively prohibited by station Standard Operating Procedures (SOPs).

A simplified, slightly conservative, application of the exclusion clause results if one applies the MPE for current as the criteria. That is, if the measured body current is less than the MPE (24 mA per limb at the Cutler operating frequency), then the maximum current density (in a wrist or ankle) is within that allowed by the exclusion clause and exposure is allowed, even if the field exceeds the MPE.

A RADHAZ survey was done recently at the Navy's VLF station in western Australia (Harold E. Holt) (Hansen & Chavez, 1993). The VLF antenna at Holt is essentially the same as a single array at Cutler. The purpose of the survey was similar to the tests described here, in that the frequency had changed and it was desired to verify the safety of the normal operating procedures for work on the towers. Based on the ANSI standard, all the Holt towers, except tower zero, can be climbed with the array active, as long as the personnel involved stay inside the confines of the tower. It is likely that this will be the case at Cutler. Verification of this at Cutler would be useful, in that it will increase the antenna maintenance operations that can be performed, while still retaining the ability to meet the 30-minute recall.

INSTRUMENTATION

A RADHAZ survey normally consists of the measurement of the electric field, (E), the magnetic field, (H), and induced body current, (I). For the Cutler tests, the electromagnetic fields were measured by the Holaday HI 3603 field-strength meter and the HI 3616 fiber-optic remote control. This meter measures both E and H fields. The maximum measurable E field is 2000 V/m and the maximum measurable H field is 2 A/m. Several meters were used for this test. Prior to starting the measurements, they were compared by setting them up under one of the feed-cages in the active south array. The readings on all the meters used for this test agreed within the manufacturers' specified accuracy.

There were three meters supplied by the Naval Medical Research Institute Detachment (NMRI Det.) for measuring body current. One of these meters is a flat plate with a digital meter attached. It is operated like a scale in that it is placed on the ground and the person stands upon it reading the body current through the feet on the digital meter. The other two meters have the appearance of a pistol with a pointed conducting snout and an analog meter mounted at the back facing the person holding it. These meters are operated by holding the meter like a pistol and touching the object in question with snout and reading the body current from the meter. A fourth method for measuring body current used a digital multimeter connected between the person and the object. Comparison measurements were made between these meters with excellent agreement.

Currents flowing through cables were measured with the digital multimeter and a current probe. Several current probes were used. Most of the current measurements were made using Pearson current transformers, but some were made using a Fluke clamp-on current transformer that has been specially modified to be used at VLF/LF. Readings from the Fluke and a Pearson were compared and found to be the same.

These instruments were carried up the towers to make the measurements at appropriate locations on the towers.

TOWER MEASUREMENTS

Symmetry

All of the tower measurements during this test period involved transmitting from the south array while taking measurements on the bow-tie towers of the grounded north array. The two arrays have a form of symmetry such that the geometric relationships between the two arrays are exactly the same. From this symmetry, it follows that transmitting on the south array and measuring on the north array is the same as transmitting on the north array and measuring on the south array. Because of this symmetry, the results of our measurements apply equally to transmitting from either array.

The two arrays are placed next together so there is a form of rotational symmetry. The axis of symmetry is a vertical line, through the ground plane at a point located half-way between the two zero towers. If the ground plane is rotated 180° around this axis, the south array overlays exactly where the north array was and vice versa. With this transformation, each tower in one array is transformed to a corresponding tower in the other array. The corresponding tower number in the other array can be determined by adding six to the tower number, and reducing the numbers modulo 12. For example, the complementary pairs of bow-tie towers are (N5 and S11), (N7 and S1), and (N6 and S12). Thus, measurements on N5 with the south array transmitting correspond to measurements on S11 with the north array transmitting and so on.

Measurement Methods

The electric and magnetic field measurements made by the field-strength meters are directional. Measurements for all three directions (polarizations) are required in order to determine the maximum field. The polarization measurements on the towers are shown in figure 12 and described below:

Vertical:	Ev, Hv	Vertical
Perpendicular:	Ep, Hp	Horizontal, perpendicular to tower face
Horizontal:	Eh, Hh	Horizontal, parallel to tower face

Maximum: Em, Hm Oriented for maximum reading

Note that figure 12 shows the crossbraces on the tower faces.

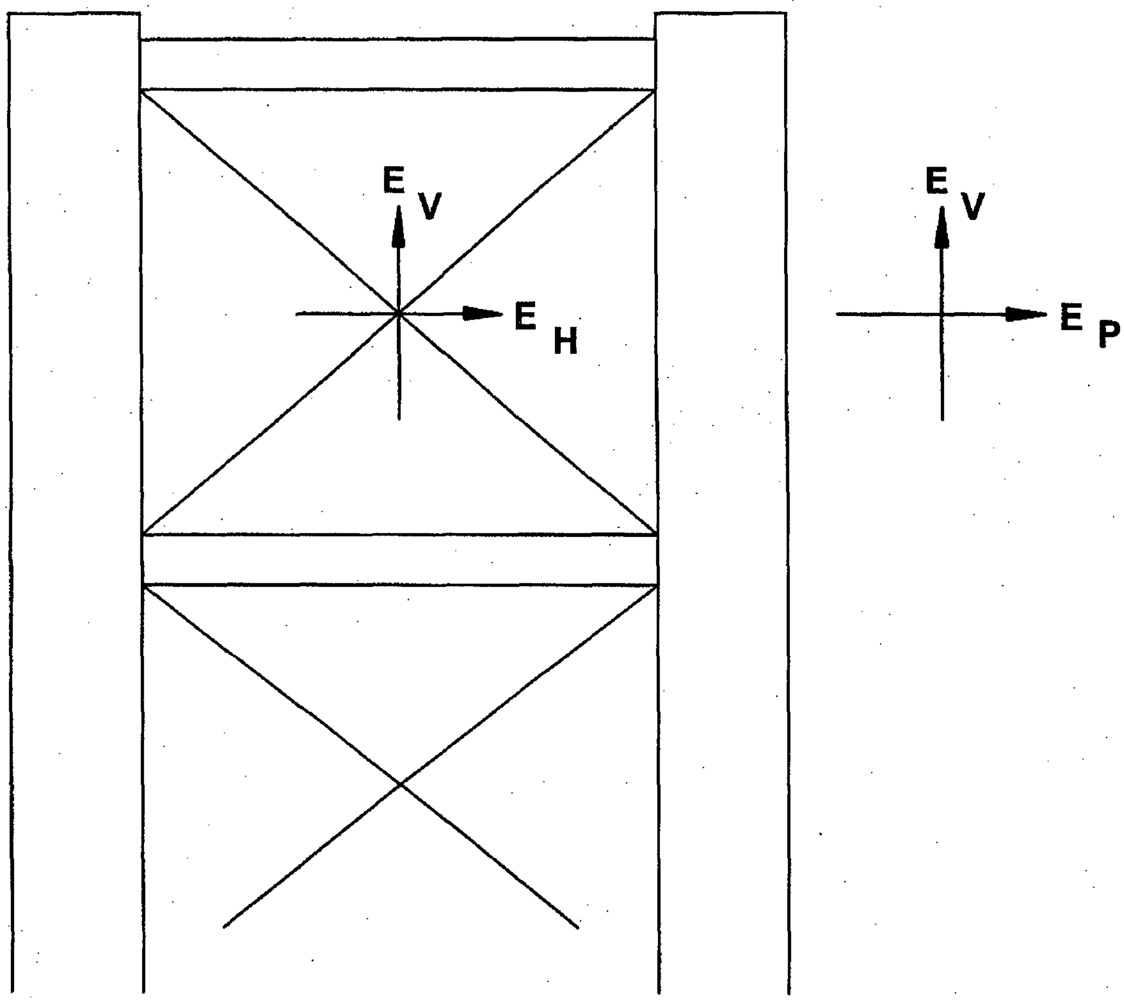

Figure 12. Radiation hazard field polarization measured.

Each of the towers has four guy levels. The towers and guys are permanently grounded, which provides partial shielding from the high fields generated by the active top-load panels. This shielding is less affective the farther up the tower one goes and the fields are greatest at the top of the tower. The plan called for measurement of the fields and currents described below. Hoever due to time constraints, these were not always measured, when it was clear that the measurements would yield values well below the levels specifieed in the safety standard.

The grounded guy wires provide shielding from the electric fields produced by the top-load panels. It was decided to make field-strength measurements at the platform just above each guy level. The test plan called for measurement of the maximum field inside the tower 1 foot from each of the three tower leg planes. The three axes of the fields outside of the tower leg planes were to be measured. These measurements were taken about chest high above the platform and approximately 18 inches outside of the tower face (figure 13). Similar measurements were to be taken at platforms with tower hazard lights. At each measurement location, if the fields were high or nuisance shocks felt, body currents were to be measured.

Figure 13. Radiation hazard field strength measurements on tower.

The tower top is different than the lower level platforms. The top guy wires attach to the tower just below the tower top at the base of the sheave platform (figure 4). The measurements were made inside and outside the tower on the sheave platform in a manner similar to the lower level platforms. However, field strengths were measured at the center and near the three edges of the tower top. Also, body current measurements were taken with a person on the top of the tower in various positions, including the position necessary to change the light bulbs for those towers with beacons on their tops (i.e., odd-numbered towers).

The station antenna mechanics helped with these measurements. In order to complete them within the time allotted, we used three teams of tower climbers. The worst case tower (N-5) was climbed by the measurement team leaders for the first set of measurements by all teams were made and recorded consistently.

Measurements

Two sets of measurements were taken during this series of tests. The first set was taken while operating in six-panel mode, at the normal power level (1850 amps antenna current). The second set was taken in four-panel mode while operating at reduced power (1600 amps), due to caution as the result of an insulator failure that occurred shortly after conversion to four-panel mode.

The measurements included a radiation hazard survey on each of the three bow-tie towers of the north array (N5, N6, and N7), a ground-based radiation hazard survey around the south array, and radiation hazard measurements on a simulated winch rigged on tower N5. All radiation hazard measurements are tabulated in appendix A. The data provided in appendix A is as measured, while the four-panel mode data provided in the section below has been scaled to 1984 amps antenna current, corresponding to the power normally radiated in six-panel mode. The section below provides a summary of the measured data tabulated in appendix A.

All findings, as far as personnel access to various areas, etc. are provided in the "Summary and Findings" section below.

Magnetic Fields. The first set of measurements were taken on tower N5 with the south array in six-panel mode. This is the worst case, since N5 is near two panels of the south array. The magnetic fields, everywhere on the tower, were less than one A/m, far below the ANSI safety limit of 183 A/m. Since this was the worst case, no further measurements of the magnetic field were necessary.

Inside Electric Fields. Similarly, the electric fields, inside the confines of tower N5, with the south array operating in six- panel mode, were all below the safety limit of 614 V/m. The highest field, inside tower N5, was 63 V/m, measured on the landing platform just below the tower top. This is nearly an order of magnitude below the safety limit. Again, since this was the worst case, no further measurements of the inside electric fields were necessary.

Outside Electric Fields. Anywhere below the top (fourth) guy level, the electric fields outside the towers were all less than 614 V/m for all three bow-tie towers in both six-panel and four-panel mode. There were some locations outside of the tower at the top where the fields were above 614 V/m, described below.

Tower N5. In six-panel mode the fields on this tower were the strongest for any of the three bow-tie area towers.

Six-Panel Mode.

Landing Platform: The maximum electric field at the landing platform was outside the one and two faces, and equal to 1440 V/m above the safe limit defined by the safety standard.

Tower Top: The maximum field measured outside the tower on the top was 1999 V/m, above the safe limit defined by the safety standard.

Four-Panel Mode. The maximum field measured anywhere on tower N5, including the tower top, was 298 V/m, well below the safe limit defined by the safety standard.

Tower N6. This bow-tie tower is farthest from the panels of the south array and the measured fields were least. All fields on tower N5 were below the ANSI limit of 614 V/m in both six-panel and four-panel mode.

Tower N7. This tower is close to one panel of the south array and has relatively high fields when the south array is in six-panel mode.

Six-Panel Mode.

Landing Platform: The maximum field at the landing platform was outside the one and two faces and was 683 V/m, slightly above the safe limit defined by the standard. The maximum field outside the zero face was 248 V/m.

Tower Top: The maximum field measured outside the tower on the top was 781 V/m, slightly above the safe limit defined by the standard.

Four-Panel Mode. The fields were below 614 V/m everywhere on the tower, except near the edge on the tower top where it was 726 V/m.

Body Currents

Tower N5

Six-Panel Mode. All body currents for a person outside of the tower below the fourth guy level were too low to be measured, including those for a person simulating changing a hazard light bulb. Since tower N5 is the worst case, no further measurements of this type were taken.

Landing Platform: The body currents measured with the person outside the tower in position to perform the sheave greasing operations were too low to be measured.

Tower Top: Body currents for a person sitting on the tower top were all less than 7 mA. Body currents were too low to measure when the person was in position to perform the normal maintenance procedures of greasing the vertical bearing and changing the beacon light bulbs. When standing on the tower top, the maximum current measured through the feet of the person was 17 mA. When standing on the tower top and touching the metal cap of the beacon, the body current exceeded 50 mA intermittently.

Four Panel Mode. Body currents everywhere were too low to be measured, except for a person standing on the tower top and touching the metal top of the beacon, when the current was 38 mA.

Tower N6

Six-Panel Mode. All body current for a person outside the tower at locations below the fourth guy were too low to be measured, including those on a person simulating light changing.

Landing Platform: The body currents measured with the person outside the tower in position to perform the sheave greasing operations were all too low to be measured.

Tower Top: Body currents for a person sitting on the tower top were all less than 4 mA. Body currents were too low to be measured for a person in the position to perform the normal maintenance procedure of greasing the vertical bearing.

Four-Panel Mode. The maximum body current recorded anywhere was 2.5 mA, measured on the tower top. The body current was too low to be measured for a person in a position necessary to grease the sheave and vertical bearings.

Tower N7

Six-Panel Mode. All body currents for the person outside of the tower below the fourth guy level were too low to be measured, including those for a person simulating light changing.

Landing Platform: The maximum body current with a person outside the tower was 2 mA, including measurements on a person in the positions required for sheave and halyard greasing.

Tower Top: Maximum body current for a person on the tower top was less than 4 mA, including measurements on a person in the positions required for greasing the vertical bearing and changing the beacon bulbs.

Four-Panel Mode. All body currents were well below the safe limit. The maximum was 4 mA and occurred when a person was standing on the tower top and touching the top of the beacon.

Nuisance Shocks

Tower N5

Six Panel Mode. Nuisance shocks were experienced by persons standing on the tower top and touching the top of the beacon.

Four-Panel Mode. Nuisance shocks were experienced by persons only when standing on the tower top and touching the top of the beacon.

Tower N6. No nuisance shock was experienced anywhere for either six-panel or four-panel panel mode.

Tower N7

Six-Panel Mode. Numerous small nuisance shocks were felt by persons standing on the tower top.

Four-Panel Mode. No nuisance shocks were experienced anywhere on tower N7 in four-panel mode.

SIMULATED WINCH (SIX-PANEL AND FOUR-PANEL MODE)

A simulated winch was rigged on tower N5 while in six-panel mode. There are many variations on how a winch might be rigged to hoist materials and equipment up the tower for painting or maintenance. We used a configuration that was familiar with our experience at the Navy's site at H.E. Holt in western Australia. Winches rigged by a contractor to perform maintenance may be different than those for which the measurements were taken. Figure 14 shows the winch rigging. Note that the winch rigging is all in one plane, which is approximately perpendicular to a radial from the center tower of the active array.

Measurements

The top of the winch line was rigged through a snatch block attached to the tower just beneath the top guy level. The conductive winch line was hauled up the outside face of the tower using a non-conductive line. The open circuit voltage and short circuit current between the cable and the tower were measured when the cable end was just below the top block. The body current when a person was between these two objects was also measured (figure 15). Similar measurements were made

when the winch cable was fully rigged, forming a loop, with the end of the cable near ground level at the winch (figure 16).

All the voltage and current measurements of both four-panel and six-panel modes are included as measured in appendix A and summarized below. Note that four-panel results given below have been scaled up to 2005 amps antenna current. The current in the winch cable was 440 mA in six-panel mode and 60 mA in four-panel mode. There are two types of problems that can result from current in the winch cable. First, if the current is large enough, it can cause damage to the cable when contact is made or broken through contact with a single strand. Such contact damage requires that the total current be equal to or greater than the fusing current of a cable strand. The currents measured in the simulated winch cable while in six-panel mode were nearly enough to cause contact damage. The second problem is that if the loop is configured to have an open circuit that becomes completed by a person touching both parts of the loop, excessive body current can result. Body currents were measured at the tower top between the cable end and the tower (figure 15) and found to be minimal in both six-panel and four-panel panel mode.

In six-panel mode, when the loop was completed by touching the end of the cable to ground or to the part of the winch cable going to the tower base, sparking was barely visible (figure 16). We completed the circuit briefly by holding the ground rod with one hand and brushing contact to the cable end with the other hand and experienced significant shocking, but no burning. The body current was excessive and not measured. The same test was done in four-panel mode and sparking could not be observed. The body current for this condition was 12.5 mA, which is less than the ANSI safety limit.

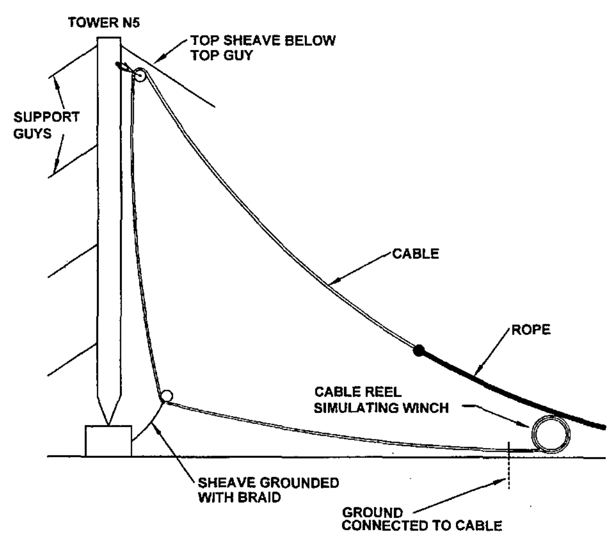

Figure 14. Simulated winch configuration.

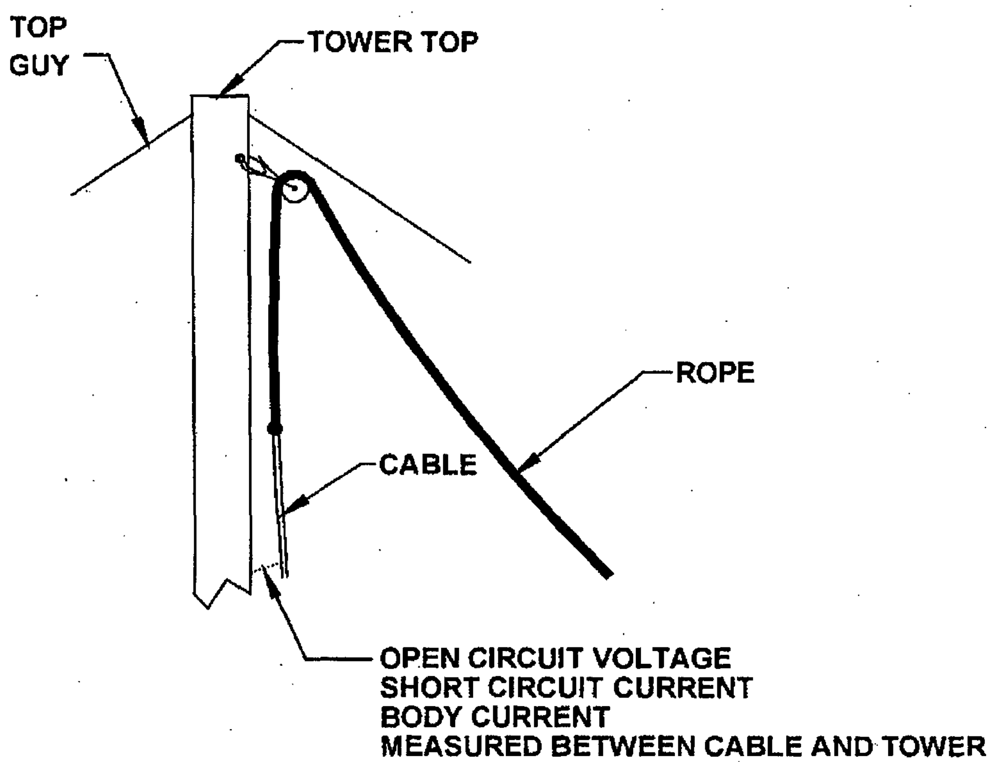

Figure 15. Simulated winch, RADHAZ measurement at tower top.

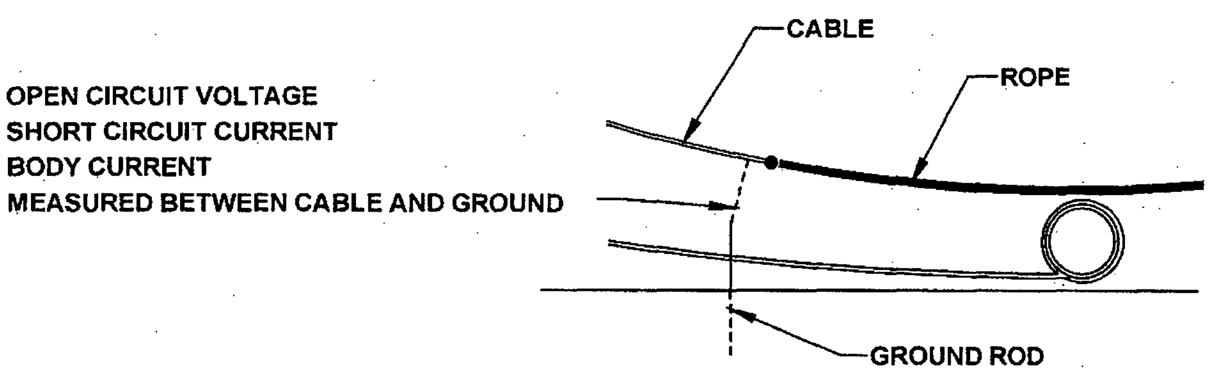

Figure 16. Simulated winch, RADHAZ measurement at winch.

GROUND MEASUREMENTS (SIX-PANEL AND FOUR-PANEL MODE)

Electromagnetic field measurements were made in the vicinity of the active south array in both six-panel and four-panel mode. The measurements consisted of the vertical E field 4 feet above the ground (Ev) and the horizontal H field (in the maximum direction) also measured 4 feet above the ground (Hh). All measurements under the feed-cages were 38 feet from the south helix house. The body currents were measured through one leg. The complete results are included in appendix A and

summarized below. The four-panel data, measured with 1600 amps antenna current, have been scaled up to 1984 amps for this summary.

Measurements

In six-panel mode, the fields measured under the feeders were all below the safety limit given in the standard.

In four-panel mode, the electric field under the four active feeders was greater than 614 V/m. The maximum field at 1984 amps would be 1168 V/m under feeder S7. However, the body currents were all below the MPE allowed by the exclusion. The maximum total body current was 4 mA under feeder S7. All fields under the array panels were well below the safety limit given by the standard.

SUMMARY AND FINDINGS

A series of tests was done at Cutler during a two-week period in September 1997. The primary purpose of these tests was to determine if the bow-tie area towers of the inactive north array could be painted while transmitting from the south array. A secondary objective was to determine the antenna parameters for the south array on 24.0 kHz. The approach used was to ground two of the panels in the south array and operate the antenna in four-panel mode. The tests included the following:

1. Rig and test four-panel mode on south array
2. Measure Antenna Impedance Parameters (both modes)
3. Measure effective height and radiated power (both modes)
4. Perform radiation hazard survey of N5, N6, & N7 (both modes)
5. Perform radiation hazard survey around the south array (both modes)

All tests were successfully completed despite an insulator failure during the test period.

CONFIGURE AND TEST FOUR-PANEL MODE

Four-panel mode was successfully configured and operated on the south array. In four-panel mode, at 24.0 kHz, with the reactor operating, the south array can radiate the same amount of power as normally radiated in six-panel mode. The configuration to four-panel or back to six-panel mode can be accomplished in less than 4 hours. The two panels to be grounded must be in the same antenna division.

ANTENNA IMPEDANCE PARAMETERS

The antenna parameters were successfully measured for the south array in both six-panel and four-panel mode.

RADIATION HAZARD SURVEY

The radiation hazard survey was successfully completed on the three bow-tie towers of the north array and around the south array with the south array in both six-panel and four-panel mode.

Six-Panel Mode

The following conclusions follow from measurements made with the south array operated in six-panel mode on 24.0 kHz at 1850 amps antenna current and the north array grounded:

1. Tower N6 can be accessed inside and outside everywhere, all normal maintenance procedures can be performed.
2. Towers N5 and N7 can be accessed inside and outside anywhere below the top guy level. Outside the tower above the top guy level, especially on the tower top, the possibility of nuisance shock exists. Personnel should minimize the amount of time spent outside in this area and especially should not stand up on the tower top. Personnel should wear gloves while working in this area.

3. All normal maintenance procedures can be performed on all three bow-tie area towers of the north array with the south array in six-panel mode.
4. Based on the fact that the fields inside the bow-tie area towers are very low and our experience with the Holt towers, it is likely that all towers (except tower zero) in an active array can be climbed within the tower to any level.

Four-Panel Mode

The following conclusions follow from measurements made with the south array operated in four-panel mode at 24.0 kHz with 1984 amps antenna current and the north array grounded:

1. The bow-tie area towers, especially N5 and N7, have much lower fields when in four-panel mode than when in than in six-panel mode.
2. All towers in the inactive north array can be safely accessed everywhere by personnel and all normal maintenance procedures can be performed.

Simulated Winch

1. A simple winch can be safely rigged on the bow-tie towers in either six-panel or four-panel mode, provided proper grounding and safety procedures are observed. In six-panel mode there is danger of significant shock, if proper safety grounds are not used. In four-panel mode, the danger of significant shocks is minimal.
2. Proper safety and grounding procedures include the following:
   a. The winch must be well-grounded.

   b. All blocks carrying the winch line must be properly grounded across connecting hardware using braid.

   c. The free end of the winch cable must be grounded by a safety ground before it can be touched safely.

   d. All personnel involved with the rigging shall wear gloves.
3. The tower block must be located below the top guy level. For towers N5 and N7, the plane formed by the winch cable should be approximately perpendicular to a radial from tower S0.
4. Complicated rigging, such as that being used by the painting contractor on the north array during these tests, should not be used on the bow-tie towers when the other array is in six-panel mode.
5. We believe it is safe to install and operate complicated rigging, such as is being used by the painting contractor, on all three bow-tie area towers. However, it is prudent to test the rigging on tower N5 after installation before using it.

Ground Measurements

There are no restrictions for access under the active array panels. However, no work should be authorized that involves large vehicles such as cranes or long conductors such as cables.

Normal access to the area around the helix house should be allowed. However, personnel accessing this area should be made aware of the possibility of nuisance shocks, especially when touching rubber tired vehicles. These shocks can be exacerbated if the ground is wet.

CONCLUSIONS

See executive summary.

RECOMMENDATIONS

See executive summary.

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APPENDIX A

RADIATION HAZARD MEASUREMENTS

Radiation hazard measurements were taken for the VLF Cutler antenna while transmitting in six-panel mode and in four-panel mode. The six-panel mode data were obtained at the normal power level that requires 1850 amps antenna current. The four-panel results were obtained while operating the antenna at reduced power corresponding to 1600 amps antenna current. Operation at this lower power was considered prudent because of an insulator failure that happened shortly after converting to four-panel mode. The radiation hazard measurements included a survey on each of the three bow-tie towers of the north array (towers N5, N6, and N7), a ground-based survey around the south array, and measurements involving a simulated winch, which was rigged on tower N5. All radiation hazard measurements obtained in this way are tabulated in this appendix.

TOWER MEASUREMENTS

Six-Panel Mode

Radiation hazard measurements were made on the three bow-tie area towers of the grounded north array (towers N5, N6, and N7) with the south array operating in six-panel mode at full power corresponding to 1850 amps antenna current.

One set of measurements was taken on tower N5 with the south array in six-panel mode. This is the worst case since tower N5 is close to two active panels of the south array. For this case, the measured magnetic fields, everywhere on the tower, were less than one A/m, far below the ANSI safety limit of 183 A/m. Similarly, the electric fields, measured inside the confines of the tower, were low. The highest inside field was 63 V/m, nearly an order of magnitude below the safety limit. This value was measured on the landing platform just below the tower top. Since the H field everywhere and the E field inside the tower were well below the hazard limit for the worst case, it was not necessary to make further measurements of these parameters for other conditions.

In the tables below, (nm) stands for not measured, usually because it was possible to infer that the measured value would be well below the standard limit of 614 V/m; (um) means that the value was too low to be measured because it was below the noise level in effect not significantly different than 0. **Red bold** numbers reflect values are above the safe limit given in the standard.

Table A-1. Tower N5 radiation hazard field strength measurements in six-panel mode (1850 amps).

	Face 0 (V/m)			Face 1 (V/m)			Face 2 (V/m)		
Location	Ev	Eh	Ep	Ev	Eh	Ep	Ev	Eh	Ep
1st light, 1 platform below 1st guy	7	5	10	30	26	30	34	25	51
Platform above 1st guy	19	22	42	54	52	90	65	52	111
Platform above 2nd guy	68	52	123	98	103	152	92	101	140
2nd light, 2 platform above 2nd guy	101	115	163	140	158	228	148	164	246
Platform above 3rd guy	137	149	240	340	265	395	242	254	408
3rd light, 2 platforms above 3rd guy	138	174	255	225	310	431	275	292	431
Platform below 4th guy	150	148	235	342	300	333	337	365	468
Landing (Sheave) Platform Above 4th guy A. left side of sheave B. right side of sheave	 282 182	 381 280	 154 220	**700**	**796**	**1260**	**760**	**976**	**1445**
Tower top, above edge	141	315	868	380	**916**	**1999**	**1766**	**1059**	**1049**

Table A-2. Human body currents measured on Tower N5
in six-panel mode (1850 amps)

Location and Orientation	Body Current (mA)
1st light platform	um
2nd light platform	um
3rd light platform	um
Sheave platform, accessing left sheave grease fitting	um
Sheave platform, accessing right sheave grease fitting	um
Tower top, accessing top sheave grease fitting	um
Sitting on top of face 1 and touching tower top	5
Sitting on top of face 1 and touching top with one hand raised	7
Standing on top of sheave and touching tower top	5
Standing on bottom edge of top center beam and touching tower top	0.3
Foot current standing on top next to beacon with hands raised	3.7
Sitting on top at 0 leg corner and touching tower top	11
Standing on bottom edge of top beam at 0 corner one hand raised	17
Standing on center beam next to beacon and touching beacon top	**Excessive ?**
When standing on the center beam on top of the tower, with insulated shoes, we experienced occasional nuisance shocks, when touching the metal top of the beacon light. We attempted to measure the current for a person in this position, but it read 0 most of the time except for brief instants when the readings shot up over 50 mA. We could not explain this phenomena. However, standing on the tower top is not a normal position required for antenna maintenance. When the person is sitting on the tower top in the position required to change the beacon light, the body currents were too low to be measured.	

Table A-3. Tower N6 radiation hazard field strength measurements in six-panel mode (1850 amps).

	Face 0 (V/m)			Face 1 (V/m)			Face 2 (V/m)		
Location	Ev	Eh	Ep	Ev	Eh	Ep	Ev	Eh	Ep
Platform above 1st guy	13	15	20	7	7	10	7	9	11
Platform above 2nd guy	32	36	53	18	14	26	18	23	26
Platform above 3rd guy	60	66	96	27	38	44	29	37	40
Landing platform Above 4th guy A. left side of sheave B. right side of sheave	290	228	399	 44 56	 126 202	 42 20	 54 56	 85 260	 40 90
Tower top, above edge	142	284	554	156	72	255	161	305	206

Table A-4. Human body currents measured on Tower N6 in six-panel mode (1850 amps).

Location and orientation	Body Current (mA)
1st light platform	nm
2nd light Platform	nm
3rd light Platform	nm
Tower top, maximum anywhere	4

Table A-5. Tower N7 radiation hazard field strength measurements in six-panel mode (1850 amps).

	Face 0 (V/m)			Face 1 (V/m)			Face 2 (V/m)		
Location	Ev	Eh	Ep	Ev	Eh	Ep	Ev	Eh	Ep
Platform above 1st guy	nm	nm	nm	nm	nm	nm	nm	nm	nm
Platform above 2nd guy	nm	nm	nm	nm	nm	nm	nm	nm	nm
Platform above 3rd guy	nm	nm	nm	nm	nm	nm	nm	nm	nm
Landing (sheave) platform Above 4th guy A. left side of sheave B. right side of sheave	 48 35	 92 248	 37 21	340	360	**683**	320	371	**636**

Table A-6. Human body currents measured on Tower N7 in six-panel mode (1850 amps).

Location and orientation	Body Current (mA)
1st Light platform	um
2nd light platform	um
3rd light platform	um
Sheave platform, accessing left sheave grease fitting	1
Sheave platform, accessing right sheave grease fitting	2
Tower top, accessing top sheave grease fitting	um
Sitting on tower beam near 0 leg touching top	2
Sitting on beam touching metal beacon top	1
Sitting on edge near leg 1 touching tower top	0
Sitting on edge near leg 2 touching tower top	2
Tower top, maximum anywhere	4
No body currents were measured in excess of the limit allowed by the ANSI standard. There were numerous nuisance shocks experienced by personnel when standing on the tower top. However, no shocks were experienced by personnel when sitting on the tower top.	

Four-Panel Mode

The radiation hazard measurements were repeated on the towers N5, N6, and N7 with the south array operating in four-panel mode. For reasons related to the fact that an insulator had failed early in the four-panel tests, the antenna current was set at 1600 amps. However, the measurements can be scaled to any value of current.

The actual measured data are included in the tables below. In the main body of this report it has been scaled up to 1984 amps. In the tables below, (nm) stands for not measured and (um) for values too low to be measured (i.e., below the noise floor of the instrument.). **Red bold** numbers are above the safe limit as given by the ANSI standard.

Table A-7. Tower N5 radiation hazard field strength measurements in four-panel mode (1600 amps).

	Face 0 (V/m)			Face 1 (V/m)			Face 2 (V/m)		
Location	Ev	Eh	Ep	Ev	Eh	Ep	Ev	Eh	Ep
Platform above 1st guy	nm	nm	nm	nm	nm	nm	nm	nm	nm
Platform above 2nd guy	nm	nm	15	nm	nm	20	nm	nm	23
Platform above 3rd guy	nm	nm	31	nm	nm	56	nm	nm	58
Platform below 4th guy	nm	nm	31	nm	nm	76	nm	nm	65
Landing (Sheave) platform Above 4th guy A. left side of sheave B. right side of sheave	 20 38	 114 107	 110 108	155	175	188	159	182	225
Tower top, max above edge corner beacon	 147 150 240			 205 202			 190 120		

Table A-8. Human body currents on measured Tower N5 in four-panel mode (1600 amps).

Location and orientation	Body Current (mA)
1st light platform	nm
2nd light platform	nm
3rd light platform	nm
Sheave platform, accessing left sheave grease fitting	8
Sheave platform, accessing right sheave grease fitting	8
Tower top, accessing top sheave grease fitting	9
Sitting on top of face 1 and touching tower top	um
Sitting on top of face 1 and touching top with one hand raised	um
Standing on top of sheave and touching tower top	um
Standing on bottom edge of top center beam and touching tower top	um
Foot current standing on top next to beacon with hands raised	nm
Sitting on top at 0 leg corner and touching tower top	um
Standing on bottom edge of top beam at 0 corner one hand raised	um
Standing on beam next to beacon and touching beacon top	**30**
When standing on the center beam on top of the tower, with insulated shoes, personnel experienced slight nuisance shocks when touching the top of the beacon light. The measured body current was 30 mA when standing and touching the beacon, slightly above the value allowed by the simplified version of the ANSI standard exclusion allowed at this frequency. However, standing on the tower top is not a normal position. When the person is sitting on the tower top, in the position required to change the beacon light, the body currents were too low to be measured.	

Table A-9. Tower N6 radiation hazard field strength measurements in four-panel mode (1600 amps).

	Face 0 (V/m)			Face 1 (V/m)			Face 2 (V/m)		
Location	Ev	Eh	Ep	Ev	Eh	Ep	Ev	Eh	Ep
Platform above 1st guy	nm	nm	4	nm	nm	1.5	nm	nm	1.6
Platform above 2nd guy	nm	nm	10	nm	nm	5	nm	nm	5
Platform above 3rd guy	nm	nm	20	nm	nm	9	nm	nm	9
Landing platform Above 4th guy A. left side of sheave B. right side of sheave	57	62	103	 12 15	 28 34	 16 11	 13 12	 36 32	 12 11
Top, max above edge	31			29			32		
Top, above center	18								

Table A-10. Human body currents measured on Tower N6 in four-panel mode (1600 amps).

Location and Orientation	Body Current (mA)
1st Light platform	um
2nd light platform	um
3rd light platform	um
Sheave platform, accessing left sheave grease fitting	um
Sheave platform, accessing right sheave grease fitting	um
Tower top, accessing top sheave grease fitting	um
Sitting on Top of face 0 and touching tower top	1
Sitting on top of face 1 and touching tower top	um
Sitting on top of face 2 and touching tower top	2
Standing on top of face 0 and touching tower top	um
Standing on top of face 1 and touching tower top	1
Standing on top of face 2 and touching tower top	2
Standing on bottom edge of top beam at 0 corner one hand raised	um
No nuisance shocks were felt on the tower top in four-panel mode.	

Table A-11. Tower N7 radiation hazard field strength measurements in four-panel mode (1600 amps).

	Face 0 (V/m)			Face 1 (V/m)			Face 2 (V/m)		
Location	Ev	Eh	Ep	Ev	Eh	Ep	Ev	Eh	Ep
Platform above 1st guy	nm	nm	8	nm	nm	18	nm	nm	15
Platform above 2nd guy	nm	nm	29	mm	nm	48	nm	nm	38
Platform above 3rd guy	nm	nm	50	nm	nm	82	nm	nm	72
Landing (sheave) platform Above 4th guy A. left side of sheave B. right side of sheave	32 142	52 120	89 81	138	199	396	136	159	282
Tower top, above Edge beacon	63 230	159	228	7	220	586	29	220	498

Table A-12. Human body currents on Tower N7 in four-panel mode (1600 amps).

Location and Orientation	Body Current (mA)
1st light platform	um
2nd light platform	um
3rd light platform	um
Sheave platform, accessing left sheave grease fitting	1.0
Sheave platform, accessing right sheave grease fitting	1.1
Tower top, accessing top sheave grease fitting	1.1
Top sitting on beam touching beacon top	1.3
Top standing on beam touching beacon top	3.0
Sitting on edge near leg 0 touching tower top	1.1
Sitting on edge near leg 1 touching tower top	1.3
Sitting on edge near leg 2 touching tower top	1.6
No currents were in excess of the simplified safe limit given by ANSI. No nuisance shocks were felt on the tower top.	

SIMULATED WINCH (SIX-PANEL AND FOUR-PANEL MODE)

A simulated winch was rigged on tower N5 while in six-panel mode. There are many ways that a winch can be rigged to hoist materials and equipment up the tower for use by personnel painting or performing maintenance. We used a configuration that was familiar with our experience at the Navy's site at H. E. Holt in western Australia. Winches rigged by a contractor could well be in a different configuration. The rigging for the winch is shown in figure 14. Note that the winch rigging is all in one plane, which was approximately perpendicular to a radial to center tower of the active array.

The top of the winch line was rigged through a snatch block rigged just beneath the top guy level. The conductive winch line was hauled up the outside face of the tower using a nonconductive line. At the top of the tower, the voltage between the end of the conductive line and the tower and the short circuit current between the conductive line and the tower were both measured (figure A-1). Similar measurements were made when the winch cable was completely in place, running all the way back down to the ground, forming a large loop (figure A-2). The currents flowing in the sheave ground cable at the tower base were also measured. All the voltage and current measurements for both four-panel and six-panel modes are included in table A13.

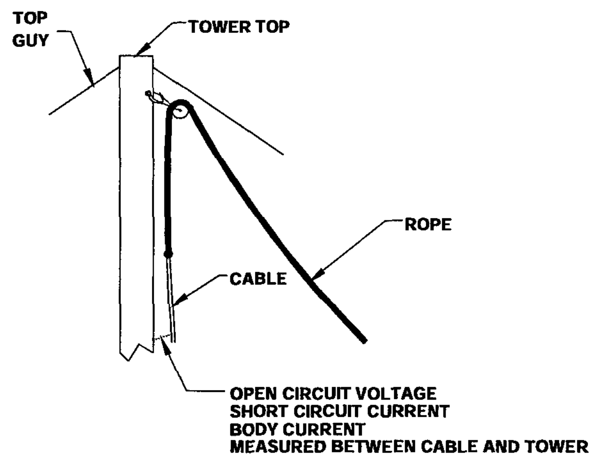

Figure A-1. Simulated winch, RADHAZ measurement at tower top.

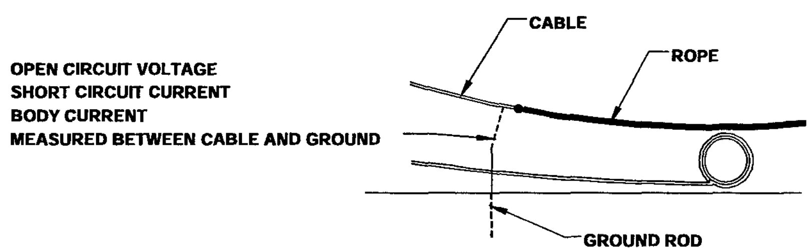

Figure A-2. Simulated winch, RADHAZ measurement at winch.

Table A-13. Simulated winch measurements on Tower N5 in six-panel mode and four-panel mode.

Location, Configuration, & Measurement	Six-Panel	Four-Panel
Platform below top guy, end of cable just below sheave, not touching tower anywhere		
voltage between cable end and tower	1.5 volts	4.8 Volts
short circuit current between cable end and tower	26 mA	34 mA
body current between cable and tower	um	um
Platform below top guy, cable completely rigged and grounded at end near tower, not touching tower anywhere		
Voltage between cable and tower	um	nm
Short circuit current between cable and tower	29 mA	nm
Body current between cable and tower	um	nm

Table A-13. Simulated winch measurements on Tower N5 in six-panel mode and four-panel mode. (Continued)

Location, Configuration, & Measurement	Six-Panel	Four-Panel
Platform below top guy, cable completely rigged and grounded at end near winch, not touching tower anywhere		
Voltage between cable and tower	um	nm
Short circuit current between cable and tower	59 mA	nm
Body current between cable and tower	um	um
Platform below top guy, cable completely rigged and grounded at end near winch but with winch moved out to 450' from the tower.		
Voltage between cable and tower	um	nm
Short circuit current between cable and tower	160 mA	nm
Body current between cable and tower	um	nm
At Winch (Figure 16). Winch completely rigged to form loop but opened at winch.		
Voltage between cable end and ground	76 Volts	8.6 Volts
Short circuit current between cable end and ground	440 mA	60 mA
Body current between cable end and ground	**Excessive**	10 mA

A large loop is formed by the winch cable running up the tower and back to the winch location (figure 16). While operating in six-panel mode, if the loop circuit was completed by touching the end of the cable to ground, or to the part of the winch cable going to the tower base, sparking was barely visible. We completed the circuit briefly by holding the ground rod with one hand and brushing contact to the cable end with the other hand and experienced significant shock (but no burning). The body current was excessive, as indicated by a fairly strong shock experienced and, for this reason, it was not measured. The same test was done in four-panel mode and sparking could not be observed and, as noted in the table, the body current was 10 mA, less than that allowed by the standard.

GROUND MEASUREMENTS (SIX-PANEL AND FOUR-PANEL MODE)

Electromagnetic field measurements were made in the vicinity of the active south array in both six-panel and four-panel mode. The measurements consisted of the vertical E field 4 feet above the ground (Ev) and the horizontal H field (in the maximum direction) also measured 4 feet above the ground (Hh). All measurements under the feed-cages were 38 feet from the south helix house. The body currents were measured through one leg. The results are summarized in the table A14. Note that (B.C.) stands for body current; (nm) means not measured; (um) means the value was too low to be measured, i.e., below the instrumentation noise; and (bs) means measured but not recorded, as it was well below the standard limit. **Red bold** numbers are above the safe limit as given by the standard.

Table A-14. Radiation hazard measurements on ground in six-panel and four-panel mode.

	Six-Panel			Four-Panel		
Location	Ev (V/m)	Hh (A/m)	B.C. (mA)	Ev (V/m)	Hh (mA/m)	B.C. (mA)
Under S1 feed-cage	500	off scale	1.7	49	1607	bs
Under S3 feed-cage	532	off scale	1.6	**756**	off scale	bs
Under S5 feed-cage	512	off scale	2.0	**814**	off scale	bs
Under S7 feed-cage	590	off scale	2.1	**942**	off scale	bs
Under S9 feed-cage	530	off scale	1.8	**760**	off scale	bs
Under S11 feed-cage	490	off scale	1.4	53	1545	bs
Under S1 panel center	199	356	um	25	150	um
Under S3 panel center	216	344	um	314	405	um
Under S5 panel center	240	351	um	305	486	um
Under S7 panel center	226	357	um	366	385	um
Under S9 panel center	200	376	um	264	480	um
Under S11 panel center	250	435	um	41	146	um

Even though the H field under the feed-cages was off scale for our instruments, it can be shown by calculation that the H field in these locations is well below the limit given in the standard, which is 184 A/m. Note that for the antenna operated in four-panel mode, the low fields under the feed-cages and panels 1 and 11 reflect the fact that they were grounded. Also, in four-panel mode, the electric field under the other feed-cages exceeds the standard limit of 614 V/m, but the body currents measured there were well below the current allowed by the simplified exclusion of 24 mA per leg.

SUMMARY

A summary of the tabulated data is given below.

Six-Panel Mode

Radiation hazard measurements were made on the three bow-tie area towers of the grounded north array (N5, N6, and N7) with the south array operating in six-panel mode at full power, corresponding to 1850 amps antenna current.

Tower N5. Tower N5 is close to two of the active panels of the south array and, therefore, expected to be the worst case for radiation hazard exposure when the south array is operated in six-panel mode. For this reason, measurements were first taken on Tower N5. The complete results are included in appendix A and summarized below.

Magnetic Field. The magnetic fields measured on tower N5 with the south array in six-panel mode were all less than one A/m, well below the ANSI safety requirement. This low value for the worst case configuration indicates magnetic field is not a problem and no further H field measurements were taken.

Electric Field

Inside the Tower. Similarly the maximum electric field measured inside of tower N5 was 63 V/m. This occurred on the sheave platform located just under the tower top. This field is also well below the standard and no further measurements of this type were conducted.

Outside the Tower. All fields measured at locations below the fourth guy level were well below the standard limit of 614 V/m.

Landing Platform. The fields outside the tower at the landing platform on the one and two face were up to 1440 V/m exceeding the ANSI limit of 614 V/m. However, the exclusion can be applied, if measured body currents do not exceed the safe limit. This turned out to be the case for measurements taken at the locations for all normal maintenance procedures performed outside the tower.

Tower Top. The maximum field measured outside the tower on the top was 1999 V/m. This value is above the safe limit given by the standard.

Human Body Currents

Inside the Tower. All human body currents measured on a person inside the tower were too low to be measured. No further measurements of this type were conducted.

Outside the Tower. All body currents for the person located outside of the tower below the fourth guy level were too low to be measured, including those obtained under conditions simulating light changing. No further measurements of this type were conducted.

Landing Platform. The body currents measured with the person outside the tower in position to perform the sheave greasing operations were all too low to be measured.

Tower Top. The human body currents measured with a person sitting on the tower top were less than 7 mA. With a person in the required positions to perform the normal maintenance procedures of greasing the vertical bearing and changing the beacon light bulbs, the body currents were too low to be measured. When a person was standing on the tower top, the maximum current measured through their feet was 17 mA. However, when standing and touching the metal cap of the beacon, the body current exceeded 50 mA for brief instants at intermittent intervals. This phenomena is not fully understood at this time.

Nuisance Shocks. Nuisance shocks were experienced by personnel when standing on the tower top and touching the top of the beacon.

Tower N6. Tower N6 is the north array bow-tie tower farthest from the active panels of the south array. For this reason, the radiation hazard fields were expected to be least on this tower. The measurements are tabulated in appendix A and summarized below.

Electric Field

Outside Tower. All fields measured on tower N5, including those made on the landing platform and the tower top were below the standard limit of 614 V/m.

Body Currents

Outside the Tower. All body currents at locations below the fourth guy were too low to be measured.

Landing Platform. The body currents measured with the person located outside of the tower in position to perform the sheaf greasing operations were all too low to be measured.

Tower Top. Body currents for a person sitting on the tower top were all less than 4 mA. Body currents were too low to be measured with the person in the position to perform the normal maintenance procedure of greasing the vertical bearing.

Nuisance Shock. No nuisance shock were experienced.

Tower N7. Tower N7 is located close to one of the active panels of the south array and therefore may have high radiation hazard fields when the south array is operated in six-panel mode. The measurements are summarized below.

Electric Field

Outside Tower. All measurements at locations below the fourth guy level were well below the standard limit of 614 V/m.

Landing Platform. The measured fields outside the tower at the landing platform on the one and two face were as high as 683 V/m which is slightly greater than the 614 V/m limit given by the ANSI standard. The maximum field outside the zero face was 248 V/m..

Tower Top. The maximum field measured outside the tower on the top was 781 V/m, a value slightly above the ANSI limit.

Body Currents

Outside the Tower. All body currents for the person outside of the tower below the fourth guy level were too low to be measured including simulated light changing. Therefore, these measurements were not repeated.

Landing Platform. The maximum body current measured with the person outside the tower in position to perform the sheave greasing operations was 2 mA.

Tower Top. The maximum body current measured for a person on the tower top was less than 4 mA. Body currents were too low to be measured when the person was in position to perform the normal maintenance procedures of greasing the vertical bearing and changing the beacon light bulbs.

Nuisance Shocks. Numerous nuisance shocks were experienced by personnel when standing on the tower top.

Four-Panel Mode

The radiation hazard measurements were repeated on the towers N5, N6, and N7 with the south array operating in four-panel mode. For reasons related to the fact that an insulator had failed early in the four-panel tests, the antenna current was set at 1600 amps. However, the measurements can be scaled to any value of current. The data, as measured, are included in appendix A. It is summarized below, but scaled to 1984 amps antenna current, corresponding to radiating the same power as normally radiated in six-panel mode.

Tower N5

Electric Field. The maximum field measured anywhere, including the tower top, was 298 V/m.

Body Currents. Body currents everywhere were too low to be measured, except for personnel standing on the tower top and touching the metal top of the beacon, when the measured body current was 38 mA.

Nuisance Shock. Nuisance shocks were experienced only when personnel were standing on the tower top and touching the top of the beacon.

Tower N6

Electric Field

The maximum field measured on tower N5 was 128 V/m, including the landing platform and tower top.

Body Currents. The maximum body current measured under any condition on this tower was 2.5 mA, measured on the tower top. The body currents with a person in position to do the sheave and vertical greasing operations were too low to be measured.

Nuisance Shock. No nuisance shocks were experienced.

Tower N7

Electric Field. The measured fields were below 614 V/m everywhere except near the edge on the tower top where it was 726 V/m.

Body Currents. All measured body currents were well below the safe limit. The maximum body current was 4 mA and was measured for a person standing on the tower top and touching the top of the beacon.

Nuisance Shocks. No nuisance shocks were experienced.

APPENDIX B
ANTENNA MEASUREMENTS
(EFFECTIVE HEIGHT AND IMPEDANCE)

INTRODUCTION

The antenna radiation resistance and radiated power can be calculated from the knowledge of the antenna effective height. This measurement is necessary in order to determine radiated power for coverage calculations and antenna radiation efficiency.

In part, due to the large wavelengths at VLF/LF (6 to 20 km), there is no direct way to measure antenna effective height, radiated power, and radiation resistance. Instead, these parameters are best determined indirectly by conducting an extensive field strength survey at sites located a moderate distance from the antenna, while at the same time recording antenna current. This is a time-honored technique, used since the beginning of radio. Little has changed with this technique over the years, except that the equipment now is more automated, the calibration is easier and much more accurate, and measuring the distance to each site is now easily done using GPSS. A brief discussion of the modern version of this technique is included below. A complete discussion, including the theoretical basis, is given in Hansen (1983).

The other important antenna operating characteristics can be determined by impedance measurements at the antenna terminals.

OBJECTIVE

The objective of these measurements was to determine the antenna effective height and radiation resistance of the single south array in both six-panel and four-panel mode at 24.0 kHz. From the knowledge of the antenna effective height, the radiation resistance and radiated power can be determined for the antenna operated in both of these modes. This information was needed to determine the antenna current required to radiate the same power in four-panel mode as normally radiated in six-panel mode.

A secondary objective was to determine the antenna impedance characteristics when the antenna is operated in four-panel and six-panel modes. Primarily, the total or gross antenna resistance needs to be determined in order to know how much power is being dissipated in the antenna. This information in combination with the radiation resistance can be used to determine the radiation efficiency of the antenna.

APPROACH

Two sets of field strength measurements were made while transmitting from the south array on 24.0 kHz. The first survey, done with the south array in six-panel mode, was extensive, with measurements at 39 sites, in an attempt to get an accurate value for the six-panel mode effective height. The second survey, done during the week that the south array was in four-panel mode, required measurements at a few of the same sites to accurately determine the difference between four-panel mode and six-panel mode. Considerable time is involved with finding suitable sites, making and processing the measurements. Two teams were involved in these measurements to complete this

task in a timely manner. The teams consisted of personnel from SSC San Diego* and Pacific-Sierra Research Corp. (PSR). A supplemental test plan for these measurements is included in appendix C.

The primary responsibility for the helix house impedance measurements was taken by PSR with support from SSC San Diego* and the station forces.

EFFECTIVE HEIGHT

Theory

In theory, either the electric field or the magnetic field could be measured to estimate the effective height of the antenna. We measure the magnetic field because it is much less disturbed by trees, buildings, etc. The formula for the magnetic field at the surface of the earth radiated by an electrically short monopole is

$$H(d) = \frac{I\,h_e}{\lambda r}\left\{1+\left(\frac{\lambda}{2\pi d}\right)^2\right\},$$

where I = antenna current,

h_e = monopole effective height,

d = distance from antenna,

λ = free space wavelength, and MKS units are used.

This formula strictly applies to the field at the earth for an infinitesimal antenna radiating over a flat perfectly conducting earth. However, provides adequate estimates of the effective height for VLF/LF antennas, on the earth, when the field is measured near the surface of the earth, at ranges between several antenna heights out to 20 km or more, depending upon frequency, ground conductivity, and terrain. The quantities to be measured for each site are (1) magnetic field; (2) antenna current (at the same time); and (3) distance from antenna center. The measured values are substituted into the formula and it is solved to determine effective height.

The measurement errors in magnetic field and antenna current are small. The distance measurement errors are small now that the military version of the global positioning satellite system (GPSS) is available, which has a position error of less than 10 meters. Errors caused by perturbations to the magnetic field, due to terrain variation and local conducting objects, can be considerable. In order to mitigate this effect, measurements are made at many sites at diverse locations and distances and the results processed statistically (i.e., averaging). Several criteria are used to try and eliminate invalid data points. These include local field variation, null direction, and the difference of the reading at a site from the overall average. In our experience, the latter is the most useful.

The magnetic field measurements are converted to radiation resistance for this processing in the following way. First the measured magnetic field and antenna current are substituted into the above equation and it is solved for effective height.

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* formerly Naval Command, Control and Ocean Surveillance Center RDT&E Division

Radiation resistance R_r is calculated from h_e by the following formula:

$$R_r = 160 \cdot \{\frac{\pi \cdot h_e}{\lambda}\}^2, \qquad \text{(B-1)}$$

where λ is the free space wavelength.

The radiation resistance data are filtered to remove points that differ from the mean by more than three standard deviations. The mean of the remaining points provides an estimate of the radiation resistance. Averaging the radiation resistance is the same as taking the rms value of the measured field strengths, which is technically the correct method to determine radiated power, hence, radiation resistance, and effective height (Hansen, 1983a). Although this method usually provides effective height estimates that differ little from the results of directly averaging the effective heights (which is the method used for previous field strength surveys at Cutler).

The sample mean and standard deviation, ($\overline{R}_r$, σ), are calculated in the usual way. The standard deviation of the mean, (σ_m), is given by the sample standard deviation ,(σ), divided by the square root of the number of independent measurements, (N) (Young, 1962).

$$\sigma_m = \frac{\sigma}{N}$$

The estimated value of radiation resistance, $\hat{R}_r$, is then given as the mean with error bound, σ_m :

$$\hat{R}_r = \overline{R}_r \pm \sigma_m .$$

This is converted back to effective height using the inverted form of equation (B-1).

Magnetic Field Measurement

The magnetic fields are measured by using a shielded loop antenna in conjunction with a tuned RF voltmeter. SSC San Diego[*] has several special loops, known as "Blue Loops" for these measurements, made by Watt Engineering of Florence, Oregon (Birkett, 1997). The loops are mounted on a special lightweight aluminum and plastic tripod to hold the loops in position.

The loop is connected to an RF voltmeter using a 25-foot piece of double-shielded coaxial cable. Hewlett-Packard "selective level meters" HP-3586 are the RF voltmeters used for these measurements.

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[*] formerly Naval Command, Control and Ocean Surveillance Center RDT&E Division (NRaD)

Calibration. Two systems were used for the field strength measurements at Cutler and both were calibrated on the NRaD VLF/LF calibration facility, which uses a special 1-meter Helmholtz coil to generate a known magnetic field. The systems are calibrated as a matched set including the loop, selective level meter, and coaxial cable. The calibration facility and technique are described in Birkett (1997). Repeated calibration of the Helmholtz system with a standard antenna indicates that the accuracy achieved is better than 0.5 percent. This is born out by the fact that during the test period readings were taken by both systems at the same site, at the same time, and they agreed to within 0.01 dB.

Technique, The field strength measurement equipment is carried in an automobile and powered by an inverter. We attempt to find measurement sites that are at diverse locations, more or less flat and far from conducting objects that perturb the magnetic field, such as power lines, buried pipe lines, culverts, fences, etc. A four-wheel drive vehicle is often useful to increase the number of suitable sites available, and we rented one for the Cutler measurements.

At each site, the vehicle is parked and measurements are taken with the loop set up at three locations approximately 20 feet behind the vehicle. Typically, the first location is approximately in line with the center of the vehicle and the other two are 5 to 10 feet on either side of center.

Antenna Current Measurement

The antenna current at Cutler was recorded by using a Fluke digital meter and a laptop computer. The meter was connected in parallel with the existing Pearson current transformers used by the station as the antenna current monitor.

Distance Measurement

It is required to know the distance from each site to the antenna center tower in order to process the data. We use a military version of GPSS for this task with specified accuracy of 10 meters, which is increased by averaging.

First the coordinates of the antenna central tower must be determined. Typically, we climb the appropriate tower and measure the coordinates at the top, with a long averaging time, prior to starting the tests. For measurements of the south array, the center of the antenna is S0. In this case, weather and the test schedule did not allow climbing S0 to the top, so we climbed to about the 150-foot level, and took averages with a GPSS receiver on two sides of the tower. These two positions were averaged, to give the best estimate of the tower location given below.

Table B-1. Cutler south array tower zero, GPSS coordinates.

Latitude	Longitude
44° 38.240' north	67° 16.713' west

These coordinates are entered into the GPSS receivers and used for the field strength measurements as a way point labeled "Cutler S0." At each site, the GPSS receiver is placed at the center location and allowed to average for several minutes. Typically, the number of fixes used in the average

exceeded 100. These averaged locations are stored in the GPSS receiver as a numbered way point. The GPSS receiver displays the distance to the tower to tenths of km. This is recorded at each site and is useful for being sure the distance to that site is within the valid range. However, it does not have enough precision for processing the data. The ranges used for data processing are obtained by downloading the recorded numbered way points and entering them into a special computer program, developed by SSC San Diego*, that calculated the range and bearing from the central tower.

Measurements

Six-Panel Mode. An extensive field strength survey of the south array in six-panel mode was completed during the week of 8 September 1997 by the two teams (SSC San Diego* and PSR). During this survey, one site was measured by both teams at the same time in order to be sure that both systems gave the same results. The results showed that the two measurement systems agreed to within 0.01 dB.

There were a total of 39 sites at which field strengths were measured at distances varying from slightly less than five km out to nearly 30 km from the transmitter. The NRaD and PSR sites are listed in tables B-2 and B-3 along with the range and bearing to each site from tower S0. The locations of these sites are shown on the map of figure B-1. The equivalent radiation resistance for the field strengths measured at each site is plotted vs. the distance (range) from tower S0 in Figure B2 and vs. the bearing from tower S0 in figure B-3. Note that there are no field strength measurements on bearings from 60 degrees true to 250 degrees true from tower S0, corresponding to angles in the direction of the ocean.

Data from four sites (marked on figures B-2 and B-3) were eliminated, due to excessive variation in the local field strength. All the remaining data were included, as none were outside of three standard deviations from the mean. Most of the measurements were within two standard deviations of the mean. The standard deviation was 0.0457 ohms, or 23.1% of the mean. This is quite high in our experience, and we attribute this to the rugged geography of the Maine coast, with the ubiquitous salt-water land interface . Data from 35 independent measurement sites were included, which reduces the standard deviation of the mean to less than 4%.

The resulting estimate of radiation resistance in six-panel mode is

$$Rr = 0.1983 \pm .0077 \text{ Ohms},$$

and the corresponding value of effective height is

$$he = 140.1 \quad +2.8, -2.7 \text{ meters.}$$

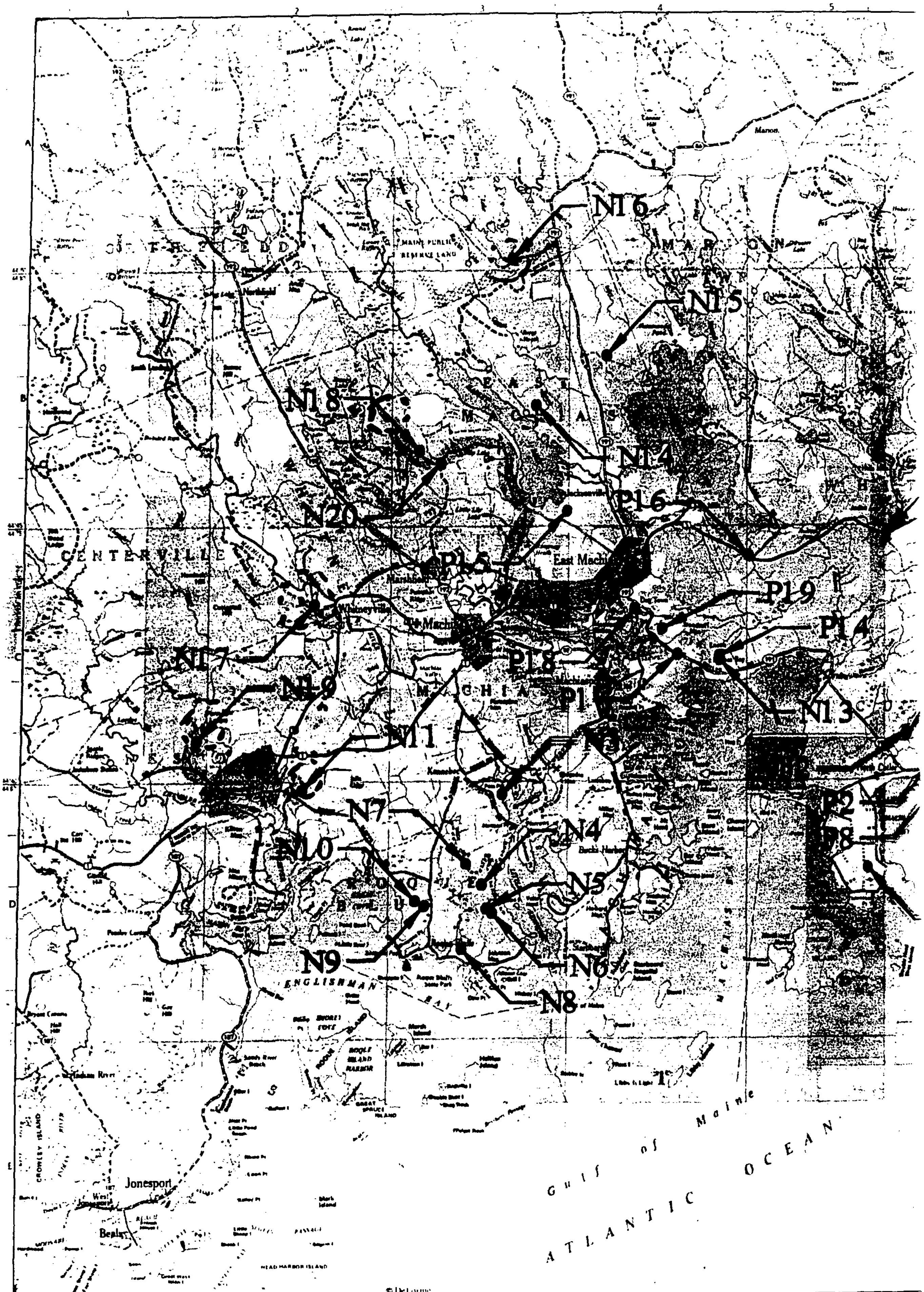
* formerly Naval Command, Control and Ocean Surveillance Center RDT&E Division (NRaD)

Table B-2. SSC San Diego field strength sites.

Site	GPSS Mark	Range m	Bearing deg T	Lat. N 44° +	Long. W 67° +	Remarks
S0	16	0	-	38.240'	16.710'	"S0" Cutler South Tower Zero
N1	15	5,077	044	40.196'	14.025'	"Aunt Ackley's ruins"
N2	17	5,595	048	40.299'	13.515'	"Ackley's woods" first turnaround
N3	18	13,778	281	39.699'	26.929'	"Gravel yard" off Kenebeck rd
N4	19	14,246	269	37.930'	27.477'	"Dirt Tee" Heath Rd off Duck Cove Road
N5	20	14,128	264	37.464'	27.341'	"Big Rock" Heath Rd off Duck Cove Road (4WD)
N6	21	14,747	264	37.382'	27.180'	"Fallen Tree Turnaround" Heath Rd off Duck Cove Road (4WD)
N7	22	14,822	271	38.339'	27.920'	"The Elbow" Heath Rd off Duck Cove Road
N8	23	15,232	259	36.682'	28.017'	"Cove Rd" off Johnson Rd
N9	24	16,371	265	37.513'	29.051'	"Blueberry Hill #1" off Roque Bluff Rd.
N10	25	16,708	266	37.616'	29.316'	"Blueberry hill #2" off Roque Bluff Rd.
N11	26	20,971	278	39.796'	32.420'	"Chain Knott" dirt rd off Roque Bluff Rd.
N12	27	5,059	016	40.863'	15.644'	"Smugglers Field" Landing strip off 191
N13	28	9,353	324	42.320'	20.881'	"Call Lyle" Dirt road off 191 (permission required)
N14	29	20,850	324	47.323'	26.027'	"Bridge out" past end of Palmer landing Rd. (4WD)
N15	30	20,972	332	48.283'	24.037'	"Rock Quarry" dirt road off 191 N
N16	31	25,730	329	50.165'	26.694'	"Rocky Lake Beach" Dirt road off 191
N17	32	21,594	313	46.186'	28.662'	"Bear S... Junction" Logging Rd off end of Hadley Lake Rd
N18	33	22,484	312	46.430'	29.263'	"Dangerous Intersection" Logging Rd off end of Hadley Lake Rd
N19	34	25,004	281	40.768'	35.286'	"Wrecked Cabin" Dirt road off /// Rd
N20	35	22,516	295	43.417'	32.118'	"Car Seat" dirt rd past end of cross st. Whitneyville

Table B-3. PSR field strength sites.

Site	GPSS Mark	Range m	Bearing deg T	Lat. N 44° +	Long. W 67° +	Remarks
P1	2 (7)	10,494	318	42.432'	22.050'	W of 191, logging rd S of swamp, 1.4 miles twds Cutler fm cripple creek farm
P2	3 (8)	4,587	033	40.320'	14.833'	End of side rd off 191, thru split in guard rail appx 1 mi from turn off to site
P3	4 (9)	5,427	034	40.666'	14.414'	Paved rd N of 191 near Fundy bay, stay left @ 3-way fork, cross river on "bridge"
P4	5 (10)	5,593	040	40.559'	14.006'	See #3, @ 3 way fork
P5	6	6,307	040	40.851'	13.654'	See #3, @ 3 way fork bear right to middle of blueberry field
P6	7	5,940	042	40.638'	13.732'	See #6, beginning of blueberry field, 100 yards before sign
P7	8	5,650	041	40.526'	13.886'	Returning fm #6, where gravel rd splits on return
P8	9	5,152	042	40.311'	14.114'	Returning fm #7 at clearing on gravel rd
P9	10	12,658	060	41.610'	08.387'	Holmes Cove, 191 4.2 miles past NE Cutler, right to end of gravel rd near ocean
P10	11	12,177	057	41.865'	09.032'	*About halfway back to 191 fm #9 on gravel rd*
P11	12	20,841	047	45.910'	05.183'	left off 191 10.2 mi N of Cutler, logging rd, 0.2 miles in
P12	13	29,800	043	49.991'	01.323'	189, 2.9 mi E of 191, Eastlnd motel, rt on gvl rd, pst house bear right, cross field
P13	14	5,087	017	40.867'	15.596'	*Private air strip off 191 near site. At far end of strip, near log*
P14	15	9,487	324	42.401'	20.894'	N off 191 at 9.1 km range, 0.23 miles into logging rd
P15	16	17,110	319	45.252'	25.134'	Hadley Lk rd, sraight at bend, rt at end, left @ 11.9 km range, site @ knoll of hill
P16	17	12,202	339	44.369'	20.092'	1 E of E. Machias turn S on logging rd at 12.3 kM range appx 0.1 mile
P17	18	12,121	003	44.773'	16.202'	Logging rd 0.12 m S of 1. Turn on rd at 12.2 km range
P18	19	12,767	318	43.324'	23.231'	fork rt on gravel rd fm 191 appx 1 mile after turn off fm 1 towards Cutler
P19	20	11,560	319	42.935'	22.471'	Turn N fm 191 @ 11.9 km range, Gravel rd along blueberry field, turn out @ 0.2 mi


N16
N15
N18
N14
P16
N20
P15
CENTERVILLE
East Machias
P19
P14
N17
N19
P18
N13
N11
P2
P8
N7
N4
N10
N5
N9
N6
N8
ENGLISHMAN BAY
Gulf of Maine
ATLANTIC OCEAN
Jonesport
Beals
© DeLorme

MAP 26

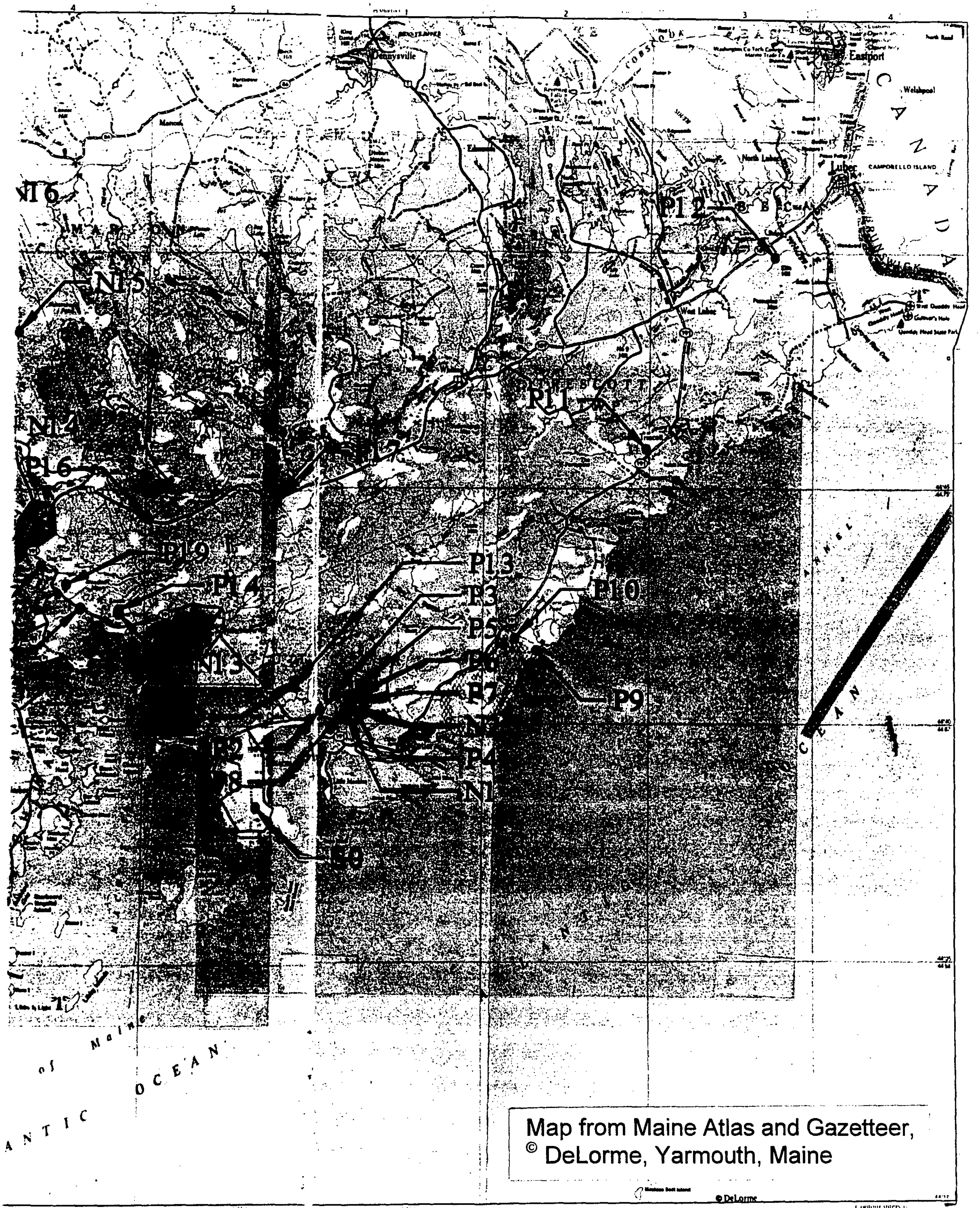


Figure B-1. Location of Cutler field strength measurement sites.

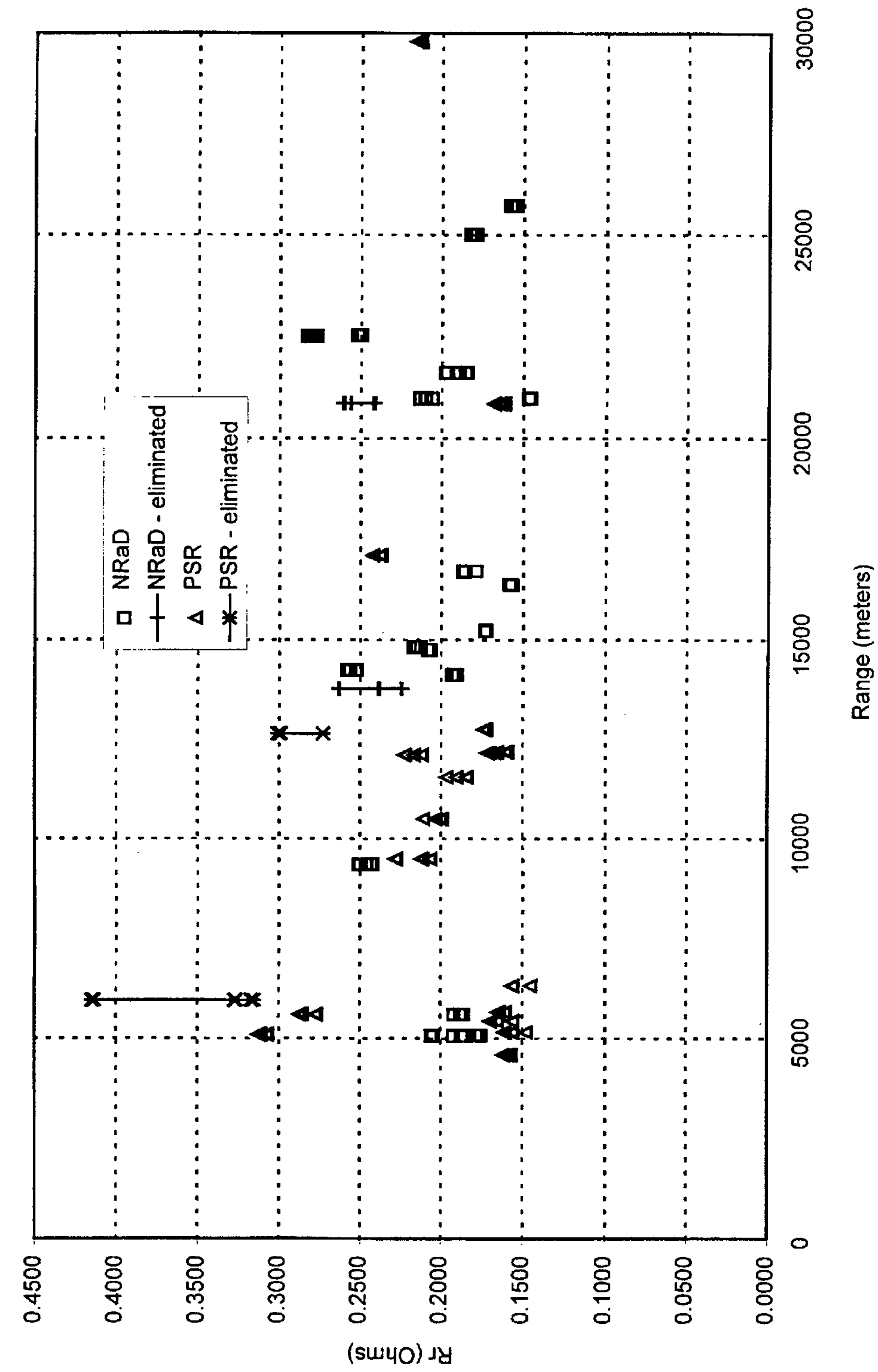


Figure B-2. Cutler south array, radiation resistance versus range (24.0 kHz, September 1997).

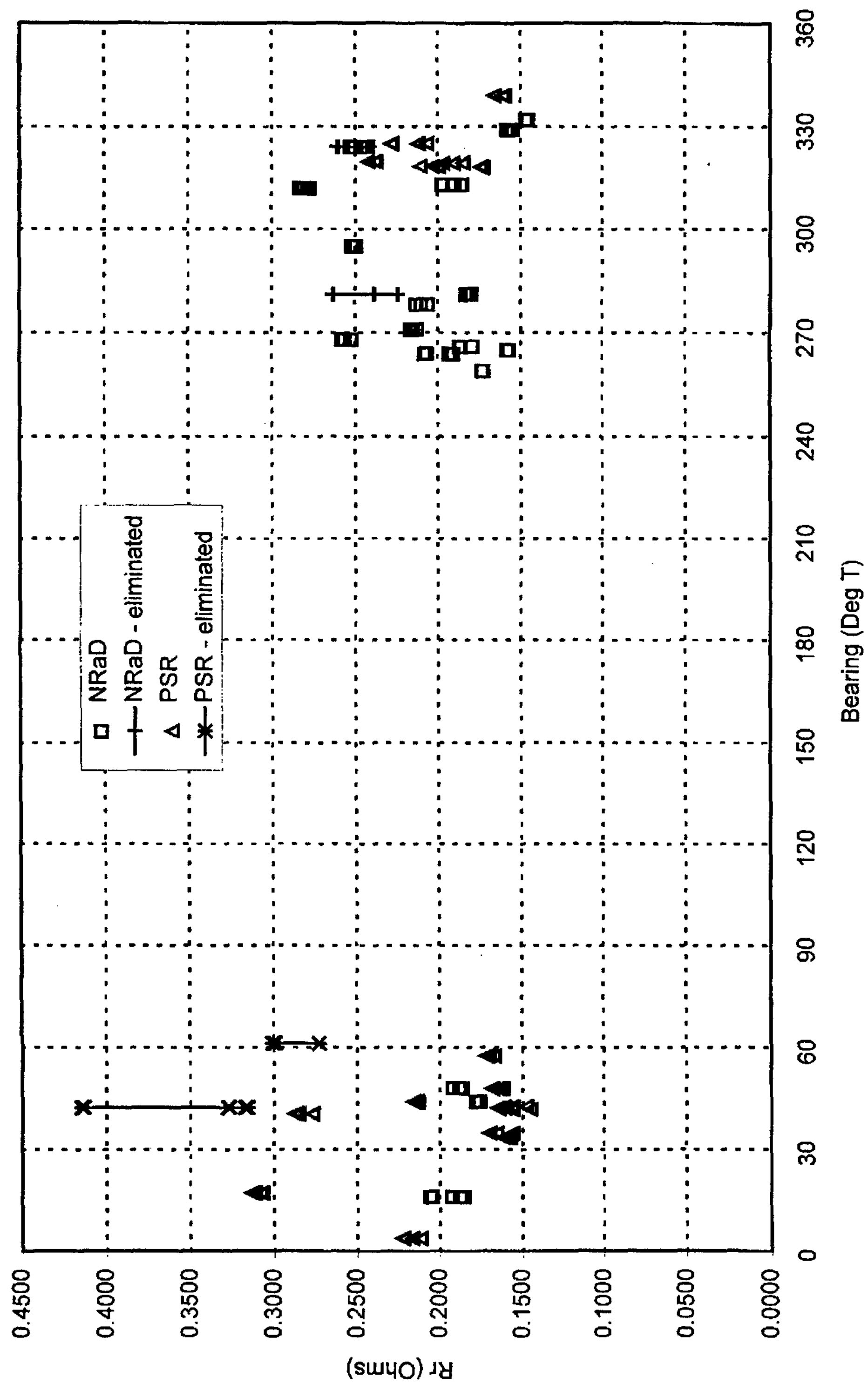


Figure B-3. Cutler south array, radiation resistance versus bearing (24.0 kHz, September 1997).

Four-Panel Mode. After conversion to four-panel mode, the field strength measurements were repeated at seven sites. The average of the ratio of these field strengths to the field strengths measured in six-panel mode normalized to the same antenna current, was used to determine the change in effective height when converting to four-panel mode. The measurements are given in table B-4.

Note that the sample standard deviation is less than 1% of the mean, in part, justifying the limited number of measurements taken. The conclusion is that the effective height in four-panel mode is reduced from that in six-panel mode by 6.90%. This agrees quite well with the percentage of current in the grounded down-leads (7.26%).

The resulting estimate for the effective height in four-panel mode is

$$h_e = 130.4 \quad +2.62, -2.52 \quad \text{meters},$$

and the corresponding estimate for the radiation resistance is

$$R_r = 0.1719 \ \pm 0.0068 \text{ ohms}.$$

Table B-4. Cutler south array four-panel ratio of normalized field strengths (four-panel/six-panel).

Site	H_4 / H_6
N5. Big Rock	0.9384
N6. Fallen Tree	0.9412
N11. Chain Knot	0.9282
N12. Smugglers	0.9356
N17. Bear S... Junction	0.9224
N19. Wrecked Cabin	0.9285
N20. Car Seat	0.9224
Average	0.9310
Standard Deviation	0.0075 (0.81 %)

Previous Measurements. Cutler was put on the air in 1961. At that time there was a proof of performance test done by Pickard and Burns, a Boston radio engineering company (Woodward, 1961). They used two carefully selected field strength measuring sites known as "monitor north", near Cooper and "monitor east," near Jonesport, to estimate the antenna effective height at several frequencies. Both of these sites were visited and found to have been encroached by buildings and power lines and no longer fit the criteria for a good field strength site.

There have been several other measurements, most of them used many different measurement sites. A partial history of these measurements is given in table B5. The column labeled "reference" refers to

references in the last section of this appendix.

Table B-5. Cutler effective height measurement history.

Reference No.	Date	Agency	Frequency (kHz)	he (m) North	he (m) South	he (m) Dual
4	Aug 61	P & B	28.5	150.5	169.0	150.5
4	Aug 61	P & B	19.4	150.5	156.0	148.0
5	Oct 63	NRL	18.6	139.2	145.0	141.0
6	Dec 64	NRL	17.8	138.2	153.6	142.2
7,8	Sep 70	NRL	17.8	137.4	144.4	143.3
9	Nov 78	NRL	17.8	136.1	140.7	136.1
9	Jan 83	NOSC	17.8	148	148	-
10	Jan 83	NOSC	24.0	-	139.7	-
This report	Sept 97	NRaD	24.0	-	140.1	-

Note that the earlier measurements tend to have considerably higher values for effective height than the later values. It is extremely unlikely that the effective height of the antenna has actually changed over time. Discussions with the antenna mechanics indicate that the winches are always hoisted to a mark placed on the halyard at the time of construction and these halyards cannot have stretched significantly.

The early values of effective height for the south array were considerably greater than for the north array. Even though the two arrays are virtually identical, it was generally believed that the south array was a much better antenna than the north array, until the 1983 SSC San Diego[†] measurements. The 1983 SSC San Diego[†] field strength survey used only a few sites and has large error bounds. However, one part of that test included a direct comparison between the two arrays. The field strength from each array, on 17.8 kHz, was measured at one site, equidistant from both arrays. This comparison showed clearly that the arrays have exactly the same effective height. Thus, in the absence of measurements, the best estimate for the effective height of the north array on 24.0 kHz is the same as the measured value measured of the south array.

The source of the difference in effective heights for the early measurements is attributed to calibration error in the measurement of the antenna currents. The value of effective height measured depends directly upon the calibration of the current monitor. If the current monitor reads low, then the value of effective height will be high. The current pick-ups, originally installed, were simple partially shielded loops approximately 1.5 feet square. At the time, calibration of this type of sensor was

[†] formerlly Naval Ocean Systems Center (NOSC)

problematical, with the most likely error being low. In the early 1980s, the current pick-ups were replaced with extremely accurate Pearson current transformers (+1/2% -0%) and digital meters.

The source of the difference between the older and the more recent measurements is also, most likely, the current probe calibration, but could also include calibration error in the measurement of the magnetic fields. The effective height is generally less for the later measurements and the north and south array values are closer. Note that the 1983 NRaD measurements at 24.0 kHz gave almost exactly the same results as the measurements reported here.

ANTENNA INPUT IMPEDANCE MEASUREMENTS

Resistance

Measurements of the antenna impedance parameters were taken at low power using a network analyzer and probe setup. Antenna system gross resistance and bandwidth were measured by connecting between the bottom of the antenna tuning elements and ground.

Experience has shown that the resistance measured at low power is usually slightly higher than when measured at high power. This is attributed to moisture collected on the antenna insulators in effect adding a shunt resistance. The transmitter has enough power to dry the insulators reducing the apparent antenna resistance. It has become our practice to measure the antenna resistance at power using the transmitter whenever possible. When available, this is the resistance value reported. The resistance at power was measured at Cutler using a special voltage divider and current transformer temporarily installed in the helix house for these tests. They were connected at the transmission line output to measure line voltage, current, and their relative phase angle. The power input to the antenna system is then calculated using the following formula:

$$P_{in} = V_{in} \cdot I_{in} \cdot Cos(\theta),$$

where P_{in} = input power,

V_{in} = input voltage,

I_{in} = input current, and

θ = phase angle between voltage and current.

Gross resistance is the term traditionally used for the total antenna system resistance, including the tuning elements and coupling coil. From the input power and antenna current, gross resistance can be calculated as follows:

$$R_g = \frac{P_{in}}{I_{as}^2},$$

where R_g = gross antenna resistance and I_{as} = antenna system current.

Self-Resonance and Static Capacitance

Antenna self-resonance and static capacitance are intrinsic antenna parameters independent of the tuning network. They were measured by using the network analyzer and probe connected directly to the antenna, with the helix disconnected. The static capacitance is the total capacitance of the system

in the limit as frequency approaches zero. We usually make this measurement at a frequency near one kHz. The self-resonant frequency is where the antenna input impedance is pure resistance without the addition of any tuning elements.

Radiation Efficiency

The antenna radiation efficiency can be derived from the antenna measurement data. It is defined as the radiated power divided by the total input power to the array. These can be calculated from the following formulas:

$$P_r = I_{as}^2 \cdot R_r \quad \text{Radiated Power}$$

$$P_{in} = I_{as}^2 \cdot R_g \quad \text{Input Power.}$$

where: I_{as} is antenna system current,

R_r is radiation resistance, and

R_g is gross antenna resistance.

The radiation efficiency factor, (η), is given by the ratio of these powers, which reduces to the ratio of two resistances:

$$\eta = \frac{R_r}{R_g}.$$

Antenna self-resonance and static capacitance are intrinsic antenna parameters, independent of the tuning network. At Cutler, they were measured by using the network analyzer and probe connected directly to the antenna with the helix disconnected. The static capacitance is the value for antenna in the limit as the frequency approaches zero. We usually make this measurement at a frequency near 1 kHz. The self-resonant frequency is the point where the antenna is resonant with no additional tuning elements.

SUMMARY

The summary of the antenna measurement data, including the effective height, antenna impedance parameters, radiation efficiency, and radiated power for the antenna current required to radiate the same amount of power as the normal 1850 amps in six-panel mode are given in table B-6.

Table B-6. South array antenna measurement results.

	Six-Panel Mode	Four-Panel Mode
Antenna effective height (m)	140.1 ± 2.8	130.4 ± 2.6
Antenna self resonance (kHz)	40.2	40.0
Antenna static capacitance (nF)	123.9	90.1
Gross resistance (ohms) measured at full power	0.2649	0.2675
Radiation resistance (ohms)	0.1984 ± 0.0077	0.1719 ± 0.0068
Antenna base reactance (ohms)	-j 35.4	-j 50.2
Antenna bandwidth (Hz) measured at low power	137.5	100
Antenna radiation efficiency (%)	74.9 %	64.3 %
Base voltage (kV)	65.5	99.7
Base current (A)	1850	1987
Radiated power (kW)	679	679

Comparison of the measurement results for six-panel and four-panel shows that grounding the two panels of one array (four-panel mode) results in a reduction in effective height and static capacitance, but an increase in loss resistance. This causes both bandwidth and efficiency to decrease and base reactance to increase, with a corresponding increase in the voltage and current required to radiate a given amount of power.

The measured effective height for four-panel mode was 6.90% less than that for six-panel mode. This corresponds quite closely to the percentage of the total antenna current that was measured in the ground leads of the two deactivated panels (7.26%).

Radiation resistance is proportional to effective height squared and is correspondingly reduced in four-panel mode. However, the total antenna resistance in four-panel mode increased slightly over that for six-panel mode. This indicates that extra losses associated with the currents flowing in the grounded panels are slightly greater than the reduction in radiation resistance. The net effect of the resistance changes is that the radiation efficiency is reduced in four-panel mode.

The static capacitance in four-panel mode was 73% of that for six-panel mode. The expected reduction in static capacitance would be 66.7%, if two (out of six) top-load panels were removed or

laid on the ground. However, as they were grounded but remained elevated they added some capacitance due to the mutual capacitance between them and the active panels.

The antenna consists of the connection of top-load panels and down-leads in parallel. Each individual panel and down-lead combination have essentially the same self-resonant frequency. The resonant frequency of the parallel combination is the same as the individual panels, independent of the number of panels. This the reason that the self-resonant frequency in four-panel mode is essentially the same as in six-panel mode.

The reduced effective height in four-panel mode requires more current to radiate the same power. The radiated power in six-panel mode with an antenna current of 1850 amps is 679 kW. To radiate the same amount of power in four-panel mode requires an antenna current of 1987 amps.

The base reactance in four-panel mode is increased by 42% over that for six-panel mode. For the same antenna current, the base voltage is increased by the same ratio. The base operating voltage for normal operation in six-panel mode is 65.2 kV rms. The base operating voltage to radiate the same power in four-panel mode will be 99.7 kV rms. This is well below the Cutler operating limit of 250 kV rms.

In four-panel mode, without the reactor, the power was limited by arcing in the copper room, to 1750 amps antenna current, corresponding to 526 kW radiated.

In four-panel mode, with the reactor, the highest current level tested was 1981 amps, corresponding to 675 kW radiated, essentially the same power normally radiated in six-panel mode. With the reactor operating, there was no limitation at 1981 Amps and more power can be radiated. Normally, the maximum power possible would have been determined during the test period. However, caution as a result of the insulator failure, resulted in a decision not to test at higher power and higher power was not necessary to meet the test objectives.

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APPENDIX C

RADHAZ AND FIELD STRENGTH TEST PLAN

Cutler 5/4 Panel Tests
Supplemental Test Plan
RADHAZ & Field Strength

Peder Hansen

SSC San Diego Code 8505

7 September 1997

OBJECTIVE

The objective of the 5/4 panel tests is to provide VLF Cutler with the capability of performing all normal antenna maintenance functions, including painting the towers in the bow-tie area, without requiring total downtime.

BACKGROUND

The VLF antenna at Cutler Maine consists of two separate arrays, each consisting of 13 towers. The antennas are top-loaded monopoles, each with its own separate helix house for tuning. For maintenance, the antenna is operated in the single array mode so that transmissions are continued on the up array while maintenance is done on the down array. This allows nearly continuous transmissions to be maintained, which is crucially important since Navy closed the other east coast VLF station at Annapolis. In the single array configuration, all the top-load panels in the inactive array, except the two in the bow-tie area can be lowered and worked on. Similarly, work can be done on all the towers of the inactive array, with the exception of the three towers that are in the "bow-tie" area where the two antennas are close together and the two top-loads intermesh.

Some years ago, when the station was on 17.8 kHz (vice 24.0 kHz presently), measurements were made on the bow-tie towers of the inactive array and the conclusion made that these towers should not be climbed nor any work done outside of the tower above the 500 foot level. This has now become station policy. It is also station policy that the bow-tie panels of the inactive array can be raised and lowered but they cannot be taken apart for maintenance while the other array is active. Thus, work on the bow-tie area towers or panels requires total station down time. The fields at 24 kHz will be lower than at 17.8 kHz and a corresponding set of measurements will be taken on the bow-tie towers of the inactive array with the other array in normal mode.

There is a tower painting project going on at Cutler scheduled over the next three years. During that time there are six towers in the bow-tie area that need to be painted. If the existing stripping and

painting technique is used, the station policy would result in several months of total down time at Cutler, which is now unacceptable.

The proposed remedy is to operate the active array in a four-panel mode whereby the two panels in the bow-tie area are disconnected and grounded at the helix house. They are inactive, not providing a source for fields, and since they are grounded, they even provide some shielding from the fields generated by the remaining active panels. Four-panel operation is not new, in that it was tested at Cutler a long time ago and is also standard operating procedure at VLF Holt, which has only one array.

The calculations indicate that the transmitter can operate adequately with four panels, especially on 24 kHz and that this will reduce the fields in the vicinity of the bow-tie towers to allow them to be worked while transmitting. The downtime expected to rig this configuration is less than 4 hours, once all the details are worked out. For this test, we have the full 12 hours of downtime, normally scheduled on Mondays, to make the change. The normal recall for this down time is 30 minutes, however, we have made arrangements with SUBLANT to allow us to have a one hour recall during the down days scheduled for this test (Monday 15 Sept, contingency day on Friday 18 September, and reconfiguration to normal six-panel mode on Monday 22 September.

MEASUREMENTS

Several types of measurements are required to verify that all this works. This supplemental test plan discusses the RADHAZ measurements and the field strength measurements

Field Strength

The field strength measurements are required in order to determine the radiated power of the antenna. No field strength survey has been taken since the station converted to 24.0 kHz several years ago and it is important to determine the actual radiated power in order to do the correct coverage calculations. Radiated power is determined by making calibrated magnetic field measurements at locations with known distances from the transmitter for distances from one twelfth of a wavelength out to distances of several wavelengths.

Two sets of these measurements will be made, i.e., normal six-panel single array and a four panel single array. The purpose is so that we can set the antenna current in the four-panel mode to give the same radiated power, as it normally has in the six-panel mode. The effective height is anticipated to be slightly less in the four-panel mode, so the required current should be only slightly greater than in the normal six-panel mode. Five-panel mode will only be used if four-panel mode cannot give the required transmitting characteristics. This is not expected based on our calculations. If five panel mode is required, these measurements will be repeated in that mode.

Two complete sets of field strength measuring equipment has been shipped to Cutler. Measurement sites are accessed by car with the field strength gear carried in the back of a car. Suitable sites are found which are as far as possible from power lines, fences, buried pipelines, etc. It is expected that measurements will be taken at approximately 30 field strength sites for the initial six-panel survey. A subset of these sites, selected on the basis of the six-panel measurements, will be used to determine the antenna current setting for the four-panel mode.

Two field strength teams will be making these measurements, consisting of NRaD personnel, Peder Hansen, Jose Chavez, Paul Pelland, and PSR Personnel Darrell Gish. However, as the field strength and RADHAZ measurements are concurrent and on the first day of each configuration, Dr. Hansen and Mr. Chavez will participate in the RADHAZ measurements. The second day of field strength measurements, Dr. Hansen and Mr. Chavez will make the measurements as well. During the second week of the tests the field strength team will be augmented by Mr. Paul Singer and Mr. Paul Pelland, both of NRaD. At some time during these measurements, a set of comparison readings will be taken at two sites, using both sets of equipment to ensure they are reading the same.

Measurement Steps:

1. Determine location of S0 (Peder, Tuesday)
2. Set up antenna current monitor (Darrell, Tuesday)
3. Start current monitor in AM (Darrell)
4. Find Field Strength Site(s)
5. Set up loop antenna in central position for that site
6. Measure and store position with GPSS, record in notebook
7. Measure null direction, record in notebook
8. Measure field strength (three independent times), record in notebook
9. Move antenna to two adjacent locations, measure and record null direction and field strength
10. Repeat steps 4-9
11. Retrieve antenna current data
12. Use PLGR program to download and calculate distances.
13. Enter currents, distances, field strength and null directions into spread sheet

RADHAZ

General

RADHAZ measurements consist of high level electric and magnetic field measurements. The ANSI standard for uncontrolled areas gives a limit of 613 Volts/m and 163 Amps per meter in the VLF frequency range. If the fields are below this level, then there is no problem for personnel access. If the fields are above this level, than a second limit is considered. This is body current and it is limited to a current in milli-amperes equal to the frequency in kHz. We have a set of meters to measure field strength and body currents.

Measurements will be taken on the towers and on the ground in areas where access is required, specifically focusing on the bow-tie area. The most important measurements are on the bow-tie towers. It is important to note that good climbing weather is required for these measurements and contingency days are planned. The station riggers will help with these measurements. We expect three teams of tower climbers to be available. For each configuration, the plan is to climb a single

tower (worst case N-5) on the first day of each configuration in order to make sure the measurement and recording techniques are consistent. On the second day, one team each will go up N-6 and N-7.

The teams will be made up from NRaD personnel, Dr. Peder Hansen, Mr. Jose Chavez and Naval Aerospace Medical Research Institute, Detachment Brooks AFB, TX. (NMRI Det.) personnel Dr. Richard Olsen, and Mr. Barry VanMatre. The NRaD personnel will have primary responsibility for the tower measurements with support from NMRI Det. and the station antenna mechanic crew. The NMRI Det. personnel will have primary responsibility for the ground based measurements, with support from NRaD and the antenna mechanic crew.

Two sets of measurements will be taken (six-panel and four-panel), with the contingency of five panel measurements, if necessary. In the six-panel mode, field strength measurements will be taken on each of the three towers. Body current meters will be carried and used to determine if it is safe to replace light bulbs on these towers in the normal mode.

Details

Each of the towers has four guy levels. Measurements will be made at the next platform above each guy level as follows. The maximum field inside of the tower (one foot from each of the three tower leg planes) will be measured and recorded. The field outside of the tower leg planes will be measured in each of the three axes. These measurements will be taken approximately chest high above the platform and outside of any other materials, such as a halyard, etc. Similar measurements will be taken at each location where a tower light needs to be accessed. At these locations, if the fields are low enough, the body currents will be measured on a person in position required to change the light bulb.

The tower top is always different. We will make the same measurements inside and outside the tower planes just below the very top of the tower. We will also make measurements at the center and near the three edges of the top platform. Again if the fields are low enough, body currents will be measured for a person in the position to change the light bulb. It is anticipated that in the six-panel mode, fields will be high enough on the top of the tower to make access unacceptable.

The schedule is given below. Note that if five panel mode is required, then measurements will be taken on both Saturday and Sunday:

First Week

September	Mon 8	Tue 9	Wed 10	Thur 11	Fri 12	Sat 13
	dwn	6 Panel	6 Panel	6 Panel	6 Panel	6 Panel
P. Hansen	T	CB - E	RH	FS	FS	C-P
J. Chavez	T	CB - E	RH	FS	FS	C-P
P. Pelland	T	E	FS	FS	FS	C-P
D. Gish	T	E - CM	FS	FS	FS	C-P
R. Olsen	T	CB-BRH	RH	RH	RH	C-P
VanMatre	T	E - BRH	RH	RH	RH	C-P
Rigger A.			RH	RH	RH	C
Rigger B.			RH	RH	RH	C

T = Travel, CB = CO Brief, E = Unpack Equipment, CM = Install Current Monitor, RH = RADHAZ Measurements, FS = Field Strength Measurements

Second Week

September	Mon 15	Tue 16	Wed 17	Thur 18	Fri 19	Sat 20
	Rig 4 Pnl	4 Pnl ops	4 Pnl ops	4 Pnl ops	Rig 5 Pnl ?	5 Pnl ops ?
P. Hansen	HH	RH	FS	C-P	C-HH	C-P
J. Chavez	HH	RH	FS	C-P	T	
P. Pelland	HH	FS	FS	C-P	C-HH	C-P
P. Singer	HH	FS	FS	C-P	C-HH	C-P
D. Gish	HH	FS	FS	C-P	C-HH	C-P
R. Olsen	C-P	RH	RH	C-P	T	
VanMatre	C-P	RH	RH	C-P	T	
Rigger A.			RH	C	C	C
Rigger B.			RH	C	C	C

HH = helix house measurements, C = contingency, P = process data, RH = RADHAZ Measurements, FS = Field Strength Measurements, T = Travel

Third Week

Sept.	Mon 22	Tue 23	Wed 24	Thur 25	Fri 26	Sat 27
	Rig 6 Pnl	6 Pnl ops	6 Pnl ops			
Hansen	HH - E	E - S	T			
P. Singer	HH - E	T				
Pelland	HH - E	T				
D. Gish	HH - E	E - S	T			

HH = helix house measurements, E = Remove & Pack Equipment, S = Ship Equipment to LaMoure, T = Travel

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The objective of the four-panel tests was to provide VLF Cutler with the capability of performing the special painting project and normal maintenance on the bow-tie area towers of an inactive array while transmitting with the other array. A secondary objective was to determine the antenna operating parameters that had not been measured since changing to 24.0 kHz.

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